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Use of the Tracking and Data Relay Satellite System (TDRSS) with Low Earth Orbiting (LEO) Satellites: A Decision Guide

by

Allan R. Topp

June 1988

Thesis Advisor: Glen A. Myers
Co-Advisor Carl R. Jones

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With increased military interest in relatively inexpensive, mission variable "lightsats" for proliferation and reconstitution purposes, an efficient means for information flow must be found. This information includes control of the mission satellite as well as retrieval of mission data. A possible selection to provide this channel is the Tracking and Data Relay Satellite System (TDRSS). This research was conducted to assemble the critical decision elements as a guide to prospective "lightsat" users of TDRSS. When TDRSS is complete, orbital coverage will be at least 85%, making this an attractive option over alternatives. Greater link ranges and signal peculiarities are limiting factors in selecting this option. Issues covered include TDRSS operational architecture, signal design and requirements, user spacecraft orbital considerations, link evaluation of all services for low earth orbits (LEO's), and cost and documentation requirements. A recommended decision path is provided for early determination of TDRSS suitability to mission needs.

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by

Allan R. Topp
Lieutenant Commander, United States Navy,
B.A., Vanderbilt University, 1975
MBA, New Hampshire College, 1980

Submitted in partial fulfillment of the requirements for the degrees of

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NAVAL POSTGRADUATE SCHOOL
June 1988

Author: Allan R. Topp
Allan R. Topp

Approved by: Glen A. Myers
Glen A. Myers, Thesis Advisor

Carl R. Jones, Co-Advisor

R Panholzer
Rudolph Panholzer, Chairman
Space Systems Academic Group

John P. Powers, Chairman
Department of Electrical and Computer Engineering

G Schacher
Gordon E. Schacher,
Dean of Science and Engineering

ABSTRACT

With increased military interest in relatively inexpensive, mission variable "lightsats" for proliferation and reconstitution purposes, an efficient means for information flow must be found. This information includes control of the mission satellite as well as retrieval of mission data. A possible selection to provide this channel is the Tracking and Data Relay Satellite System (TDRSS). This research was conducted to assemble the critical decision elements as a guide to prospective "lightsat" users of TDRSS. When TDRSS is complete, orbital coverage will be at least 85%, making this an attractive option over alternatives. Greater link ranges and signal peculiarities are limiting factors in selecting this option. Issues covered include TDRSS operational architecture, signal design and requirements, user spacecraft orbital considerations, link evaluation of all services for low earth orbits (LEO's), and cost and documentation requirements. A recommended decision path is provided for early determination of TDRSS suitability to mission needs.

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TABLE OF SYMBOLS

Biϕ:	Biphase
Biϕ-L:	Biphase level
Biϕ-M:	Biphase mark
Biϕ-S:	Biphase space
b/sec:	bits per second
dB:	decibel
dBW:	decibel relative to 1 Watt
E_b/N_o:	bit energy-to-noise ratio spectral density ratio (dB-Hz)
f_c:	transmit carrier frequency
f_o:	nominal center frequency of user spacecraft receiver
f_R:	carrier frequency arriving at the user spacecraft G gain
GEO:	geostationary orbit radius 42164 km
G/T:	antenna gain-to-noise temperature ratio (dB/K)
k:	Boltzman's constant 1.38 x 10-23 W/Hz-K
K:	Kelvin
kb/sec:	kilobits per second
kHz:	kilohertz
km:	kilometer
Mb/sec:	megabits per second
Mc/sec:	megachips per second
MHz:	megahertz
NRZ:	nonreturn to zero
NRZ-L:	nonreturn to zero level
NRZ-M:	nonreturn to zero mark
NRZ-S:	nonreturn to zero space
P_{rec}:	signal power received at the TDRS antenna from a user spacecraft
P_{req}:	signal power required at the TDRS antenna to achieve a certain level of link quality
R:	ratio between data rate and convolutionally encoded symbol rate; range between TDRS and user spacecraft range
$\ddot{R}$:	acceleration between TDRS and user spacecraft (meters/sec2)

r_E:	radius of the earth = 6.378 x 103 km
r_o:	radius of satellite orbit
SNR:	signal-to-noise ratio
T_a:	antenna temperature (K)
T_{acq}:	time to acquire
T_s:	receiving system noise temperature (K) referenced to the antenna output terminals

TABLE OF ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

ADR:	achievable data rate
BER:	bit error ratio
BPSK:	binary phase shift keying
BRTS:	Bilateration Ranging Transponder System
BW:	Bandwidth
CDR:	critical design review
Channel BW:	6 MHz for MA, 10 MHz for SSA, and 225 MHz for KSA return links
CLASS:	Communications Link Analysis and Simulation System
CTV:	Compatibility Test Van
data BW:	bandwidth in Hz equal to twice the baud rate
DG1:	Data Group 1
DG2:	Data Group 2
DOMSAT:	domestic communications satellite
DR:	data rate
EIRP:	effective isotropic radiated power (dBW)
ES:	earth station
FDR:	final design review
FEC:	forward error correction
FOV:	field of view
FSL:	NASA define constant used in return link calculations
GSFC:	Goddard Space Flight Center
GSTDN:	Ground Spaceflight Tracking and Data Network
ICD:	Interface Control Document
I channel:	data channel supported by 0 degree and 180 degree phase modulation of the carrier
IPD:	Information Processing Division
JPL :	Jet Propulsion Laboratory
JSC:	Johnson Space Center
KSA:	K-band single access

KSC:	Kennedy Space Center
K-band:	13.4 to 15.25 GHz
LCP:	left circular polarization
LHC:	left hand circular link includes either data and/or range channels provided by a TDRS forward or return service to a user spacecraft. In the case of SA service, a link is defined relative to a specific antenna on a particular TDRS. In the case of MA service, a link is defined relative to a particular TDRS.
MA :	multiple access
MIL :	Merritt Island GSTDN station
MPT :	Mission Planning Terminal
MSS :	Message Switching System
N/A :	not applicable
NASA:	National Aeronautics and Space Administration
NASCOM :	NASA Communications Network
NCC :	Network Control Center
NGT :	NASA Ground Terminal
NMI :	NASA Management Instruction
NSC :	NASA Support Committee
NSP :	NASA Support Plan
OR :	Operations Requirements (document)
OSCD:	Operations Support Computing Division
OSCF:	Operations Support Computing Facility
OSF :	Office of Space Flight
OSTDS :	Office of Space Tracking and Data Systems
OTDA:	Office of Tracking and Data Acquisition
PDR:	Preliminary Design Review
PN :	Pseudorandom Noise
POCC:	Project Operations Control Center
PSK :	phase shift keying
Q channel:	data channel supported by ± 90 degree phase modulation of the reference carrier
QPSK:	quadriphase shift keying range channel forward service channel used for transferring the PN code used for two way range measurement
RFI :	radio frequency interference

RHC:	right hand circular
SA:	single access
S-band:	2000 to 2300 MHz
SC:	spacecraft
SER:	symbol error rate
SHO:	Scheduling Operations Message (NCC to WSGT)
SIRD:	Support Instrumentation Requirements Document
SOC:	Simulations Operations Center
SQPN:	a modulation process in which the phase of the PN clock modulating the Q channel is delayed 1/2 chip relative to the phase of the PN clock modulating the I channel
SQPSK:	staggered quadriphase shift keying
SSA:	S-band single accessSTDN Spaceflight Tracking and Data Network
TDRS:	Tracking and Data Relay Satellite
TDRSS:	Tracking and Data Relay Satellite System
TN:	TDRSS Network
TT&C:	telemetry, tracking, and command
UQPSK:	unbalanced quadriphase shift keying
user SC:	user spacecraft
WSGT:	White Sands Ground Terminal
ZOE:	zone of exclusion

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I. INTRODUCTION

A. MOTIVATION FOR THE STUDY

U. S. defense efforts have become increasingly reliant on space systems for a wide variety of mission needs. Present and near-term foreseeable systems are typically highly specialized, complex, and centralized. This has led to a growing concern for their survivability and in the event of their destruction or severe degradation, a means of rapid deployment of substitute systems. Along the same lines, proliferated constellations of single mission satellites have been suggested to offer graceful degradation in a hostile environment.

One possible response repeatedly raised in the military community has been the development of small, relatively inexpensive, generic satellites which could be readily adapted to a wide range of missions and orbits. Possible missions include communications, tactical intelligence imaging, environmental sensing, signal intelligence, anti-satellite roles, and radar jamming. An example of such a general purpose vehicle is the proposed Naval Postgraduate School Orion. [Ref. 1]

All of the possible mission concepts have a common thread; they must be capable of receiving and/or transmitting information to their controlling authority. The amount of information can range from low data rate telemetry and command to extremely high data rate imaging information. In addition, some missions may require very precise position information on the satellite itself for successful mission execution. Unfortunately, such systems are typically low altitude, power limited vehicles that will come to fruition at a time of shrinking geographic ground support facilities. This will result in one of the following scenarios: substantial

recording and playback capability will have to be included in the design; data will be lost; geographic limits will be imposed on mission execution; or, a space-based relay system will have to be used.

In part anticipating such an environment, NASA designed, built, and will, on the next Shuttle, complete the launch of the Tracking and Data Relay Satellite System (TDRSS) to provide this space option. For the military planner, some military assets could be diverted to such a role, but this is quite different from their design purpose and suboptimum performance could result. TDRSS remains a premier candidate for use with small "lightsat" designs in low earth orbits (LEO).

This study assembles the pertinent decision criteria for space system designers for an early determination of the suitability of TDRSS for the proposed mission. Actual implementation would require much more exhaustive design study and rigorous cost analysis. Since no specific mission is addressed, the information provided covers a wide range of possible orbits and user power levels. Executive

B. OVERVIEW OF THE THESIS

The bulk of this thesis presents elements of the TDRSS Network that will have direct impact on the selection of this option for use with design missions. Chapter two introduces the TDRSS Network; its concept, purpose, organizational relationships, and services provided. An end-to-end data flow is traced with the description of each functional element. Actual signal design, data rate limitations, and further technical parameters are delineated in chapter three to give designers an idea of the unique scope of transponder and associated hardware design required. Mission orbit selection considerations of chapter four establish fundamental orbital relationships which must be satisfied to meet either mission needs or TDRSS technical parameters. To match communications capabilities of

the mission satellite with the TDRSS, chapter five gives an in depth link analysis of all services through the TDRSS. Planning charts based on nominal values are developed as well as precise link equations for specific mission data. Included in the analysis are the effects of using forward error correction coding when optional and linear versus circular polarization. TDRSS utilization incurs unique cost structures and documentation requirements. Chapter six gives a top level view of this process and includes coincident timeline requirements inherent in the process. The thesis concludes with a summary of the essential features and a decision hierarchy of the elements introduced in the thesis body. Several computer programs are provided in the appendices to aid in the mission analysis for the planners.

II. TRACKING AND DATA RELAY SATELLITE SYSTEM NETWORK ARCHITECTURE

A. INTRODUCTION

The Tracking and Data Relay Satellite System (TDRSS) is an ongoing expansion of NASA's Spaceflight Tracking and Data Network (STDN). This network provides a means of receiving and sending telemetry and data from orbiting satellites. TDRSS offers a vast extension of capabilities and services over the original Ground Satellite Tracking and Data Network (GSTDN). It offers both greatly expanded volumetric coverage and data transfer capability. For users, this translates to much reduced store and dump requirements for telemetry and data but, in general, higher radiated power requirements. [Ref. 2:pp. 1-1,1-2]

The TDRSS Network (TN) is the complete end-to-end data channel and has three primary functional components: user spacecraft, TDRSS, and ground support facilities Figure 2-1 shows the complexity of this entire network. For the user spacecraft (SC), blocks of interest for data load carrying are 1, 2, 9, 11, and 12. These define the functional elements which receive, process, and retransmit the data to the ultimate destination of the mission planning terminal (MPT) or project operation control center (POCC) information processing division (IPD). The remaining blocks represent support or auxiliary functions such as shuttle launch support services or the compatibility test van (CTV). These functions are either transparent to the user or are used during the project development stage and not later. A complete listing of acronyms and abbreviations can be found in the forward section of this report. [Ref. 2:p. 1-5]

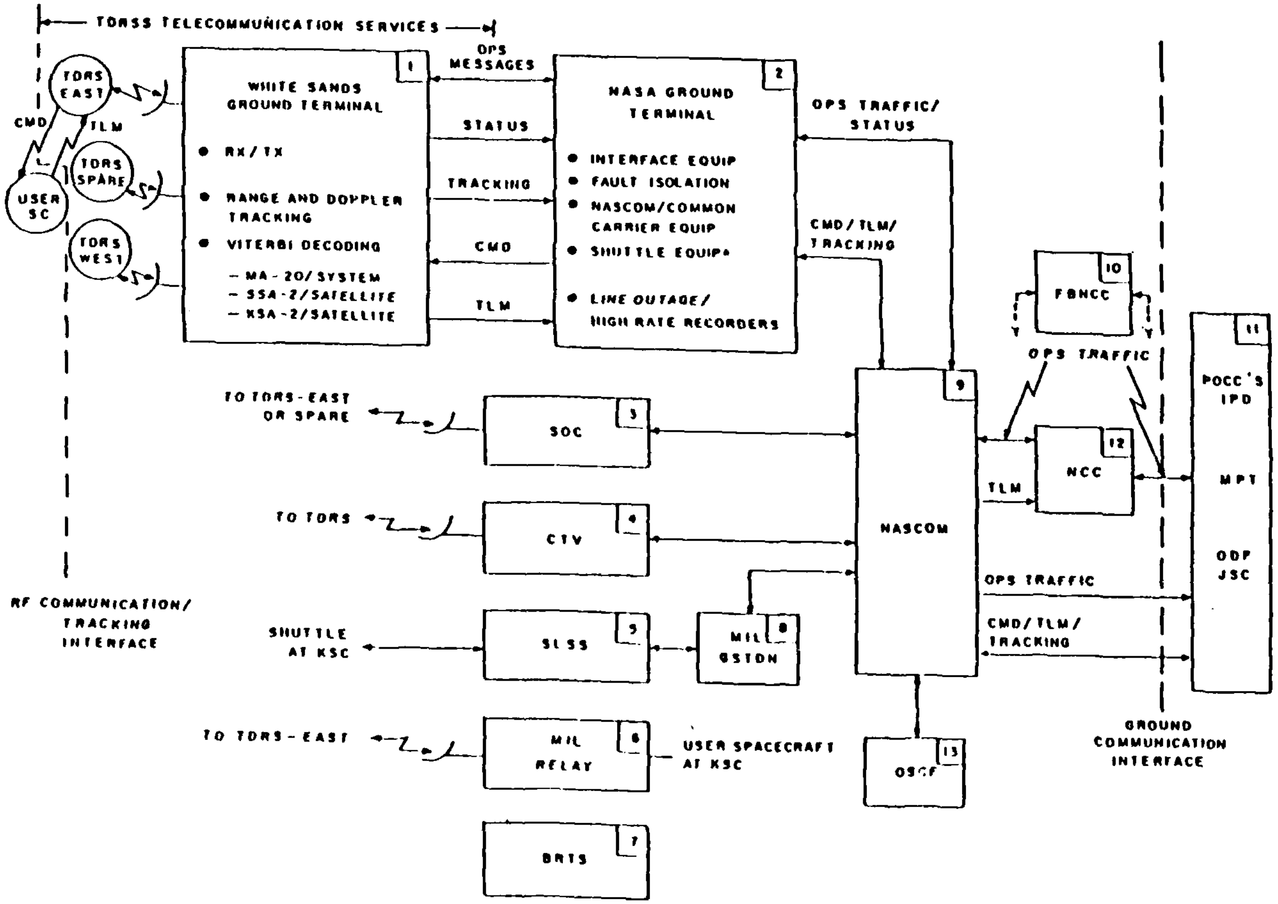


Figure 2-1
TDRSS Network

Effective control and interface of these components provide forward and return telecommunications between low earth-orbiting user spacecraft and user control and data processing facilities. In addition, scheduled tracking services in support of orbit determination are available. For user data support, a real-time bent-pipe communication concept is used. In this mode the user data stream is received on board the TDRS, translated in frequency and re-transmitted to the earth station. No processing is performed on the user data at the TDRS.

This chapter will describe in detail these components and their interface with the entire system. Additionally, those agencies and entities charged with specific duties and responsibilities will be shown with their operational relationships.

B. SPACE SEGMENT

The TDRSS segment of the TN consists of two functional Tracking and Data Relay Satellites (TDRS) in geostationary orbits. TDRS-East is located at 41° W longitude and TDRS-West at 171° W longitude with both satellites at a nominal 0° latitude. In addition, an on-orbit spare is located at 79° W longitude and another is in configuration for a rapid deployment launch. Figure 2-2 shows the versatility of the TDRSS in supporting a wide range of possible space users. Possible candidates range from very simple low altitude satellites to high data rate and high priority customers like the Shuttle. [Ref. 3:p. 3]

1. Satellites

Each TDRS is a three-axis body stabilized, momentum-biased configuration with sun oriented solar panels as depicted in Figure 2-3. At beginning of orbital lifetime (10 years), each spacecraft weighs 4732 pounds. The on orbit configuration measures 57 by 47 feet of the extended outer dimensions.

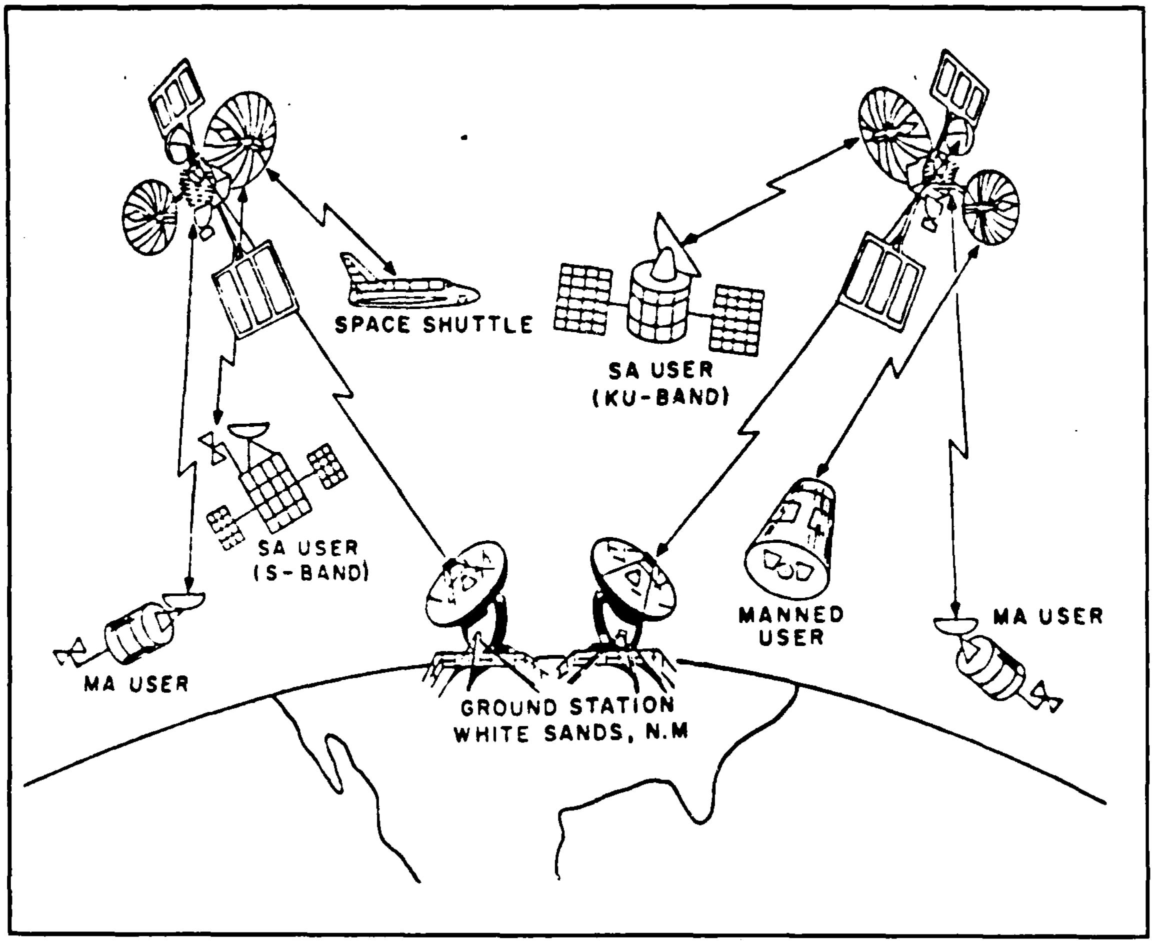


Figure 2-2
TDRSS/User Configuration

The primary payload subsystem is for telecommunications and is comprised of the equipment which performs the TDRSS and the domestic communications services. TDRSS equipment consists of the antennas and communications repeaters that relay data between user satellites and the White Sands Ground Facility. Figure 2-3 also shows the antenna layout and structure for each TDRS. Of interest for the user SC are the multiple access (MA) at S-band, which is a 30 element array of helices, and the two circular high gain antennas

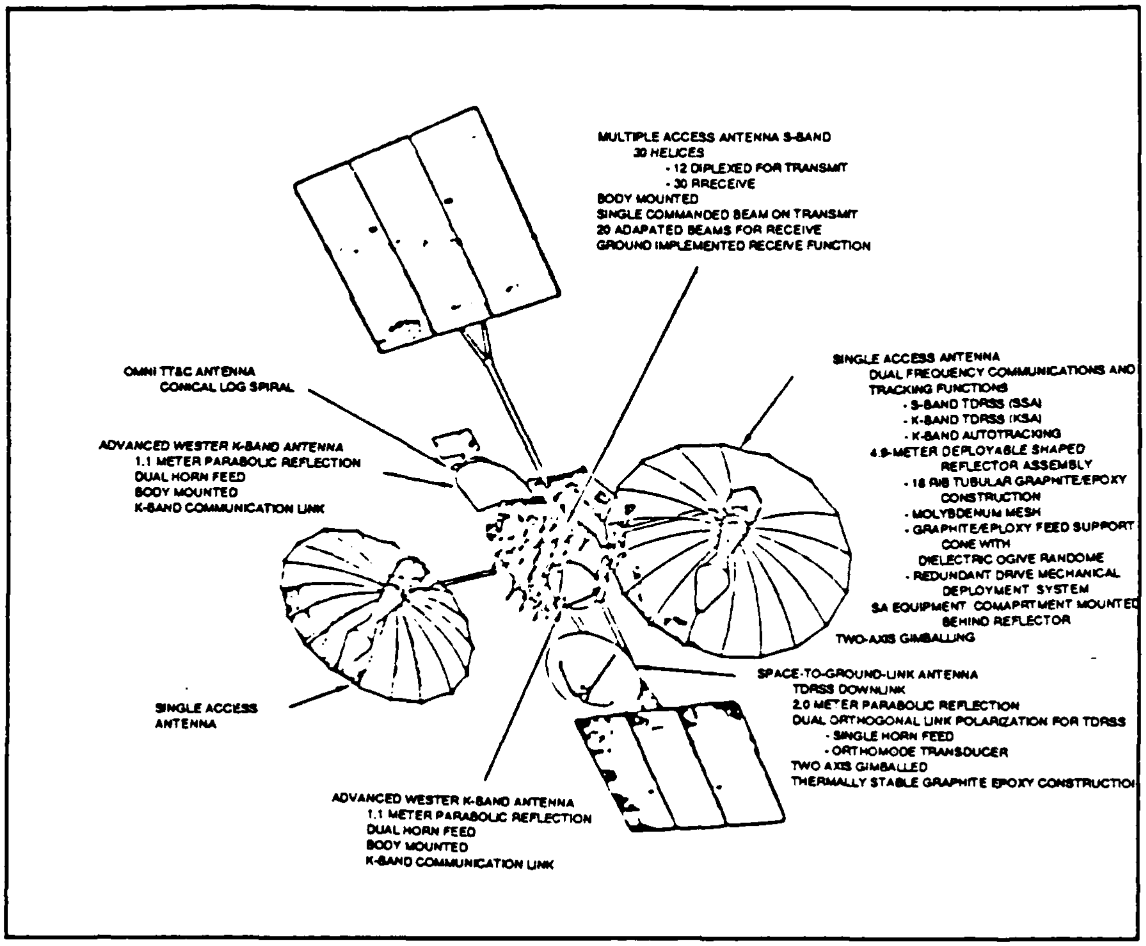


Figure 2-3
TDRS Antenna Configuration

which service both S and K-band single access (SA) simultaneously. The other antennas service support equipment and domestic traffic.

The communications services equipment consists of a 12-channel transponder providing domestic service at C-band and a four channel transponder providing domestic service at K-band. Because the TDRSS and communications services at K-band do not operate simultaneously, substantial antenna and RF conversion equipment sharing is possible. This both reduces total equipment while

providing increased levels of critical equipment redundancy. A separate C-band transponder and antenna provide the C-band communications services.

The telecommunications subsystem payload elements include:

- K-band space/ground link equipment
  - 6.6 foot gimballed antenna
  - K-band receivers, upconverters and TWTA's
- Forward and return processors
- K and S-band single access (KSA and SSA) equipment
  - Two 16 foot antennas
  - K and S-band receivers and transmitters
  - 26 watt TWTA's
- S-band multiple access (MA) equipment
  - 30 element antenna array
  - Multi-channel receivers and transmitters
- Frequency generation equipment

2. TDRSS Geometric Coverage

The TDRSS orbit configuration enables simultaneously a single ground station for both satellites and at least 85% orbital coverage for orbits from 100 to 12,000 km. This compares with 15% coverage available under the old STDN. However, due to geometric line of sight limitations a zone of exclusion exists in the general vicinity of the Indian Ocean. These zones will vary in size and duration depending on orbit altitude and inclination as depicted in Figure 2-4. Figure 2-5 is an example of an exclusion zone for a 500 kilometer orbit. Any user SC in the shaded zone will not have line of sight to either TDRS. For user spacecraft whose orbital altitude will exceed 12,000 kilometers, significant coverage gaps may result

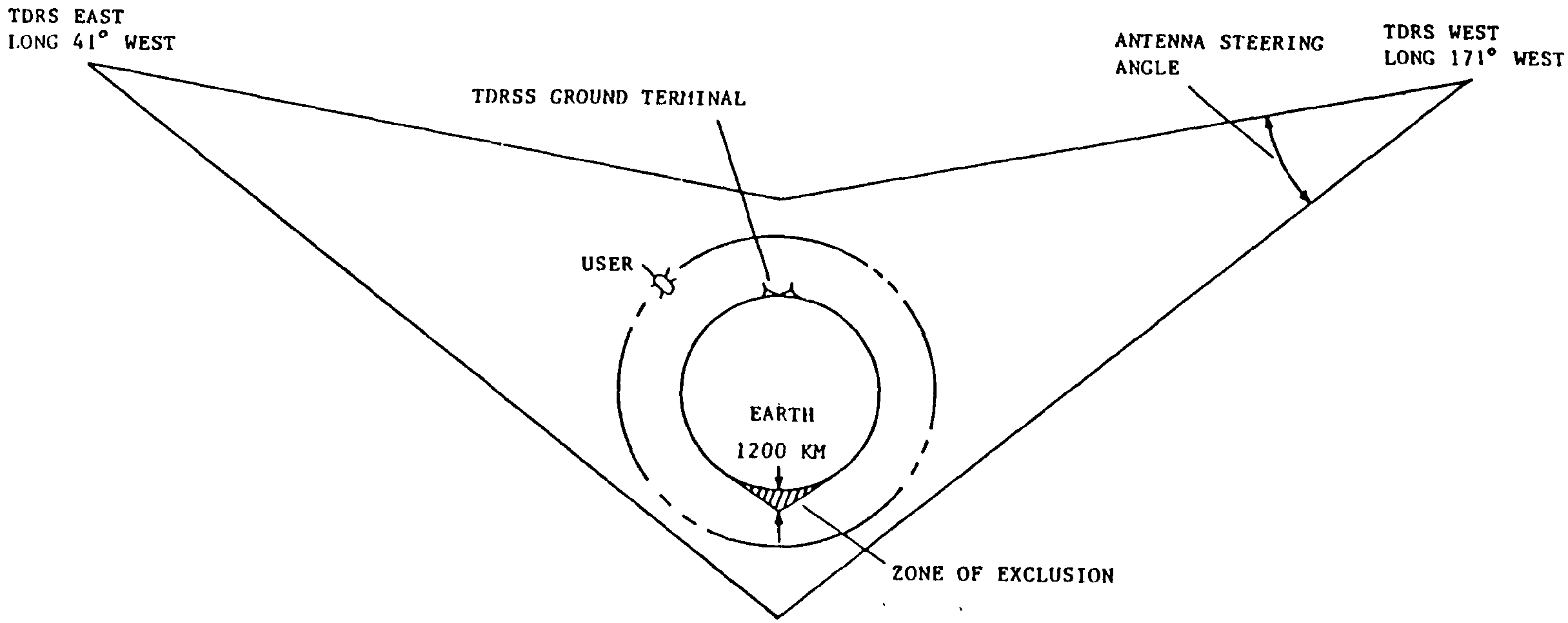


Figure 2-4
TDRSS Geographic Orientation

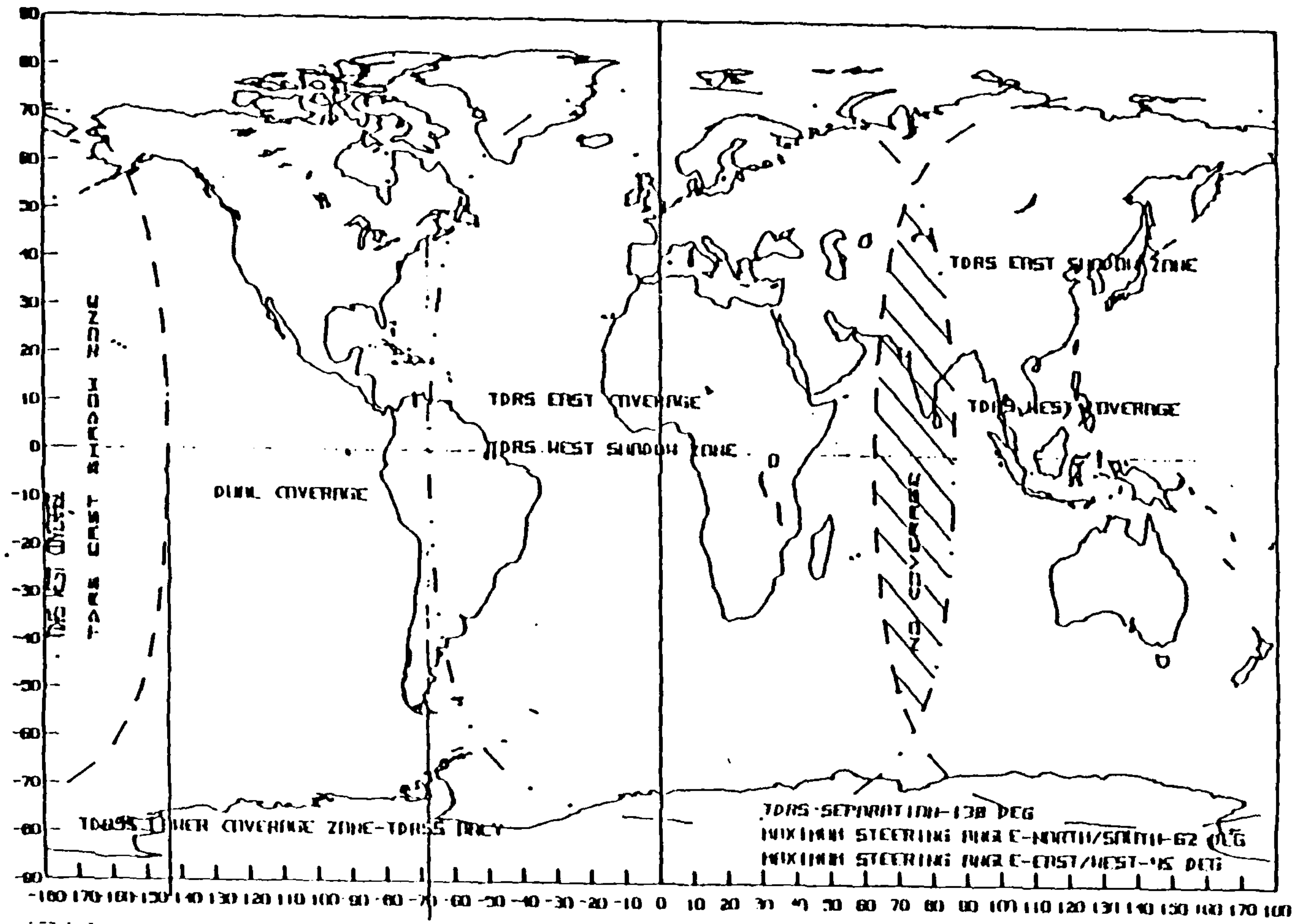


Figure 2-5
TDRSS Coverage for 500 km. Orbit

depending on orbit geometry. These gaps are almost entirely due to the antenna beamwidth and steering angle limits for the TDRS's. [Ref. 2:pp. 1-3]

In Figure 2-6, the general geometric considerations for spacecraft in excess of 12,000 kilometers are shown. For the single TDRS depicted, the intersection of conic sections defines coverage zones. Contour C is the projection on the earth's surface of the line of intersection of all possible circular orbits at a given altitude with the coverage cone. Beyond this intersection the user SC is outside of the cone of coverage. As we continue further in the orbits, another intersection line occurs as the user SC returns to coverage. Contour B is the projection of the second line of intersections. Finally, as the user SC is eclipsed by the earth, the last line of intersections can be projected as Contour A. [Ref. 2:p H-7]

Figure 2-7 is an example of TDRS-East coverage for a 20,000 kilometer user SC, and Figure 2-8, TDRS-West coverage for the same spacecraft. Combining both yields Figure 2-9 for the entire TDRSS. [Ref. 2:pp. H-8-H-10]

From this discussion, it is apparent that TDRSS coverage is well suited for the 1,200 to 12,000 kilometer range with 100% coverage. For missions outside this range, the orbital elements need strict examination for coverage availability. Orbits in this discussion have been circular, so elliptic orbits will need a more detailed analysis.

C. GROUND SEGMENT

Several key ground segment components interact to form the backbone of the TDRSS Network linking the user Payload Operations Control Center (POCC), its associated capture and processing facilities, and the user spacecraft. These elements are as follows.

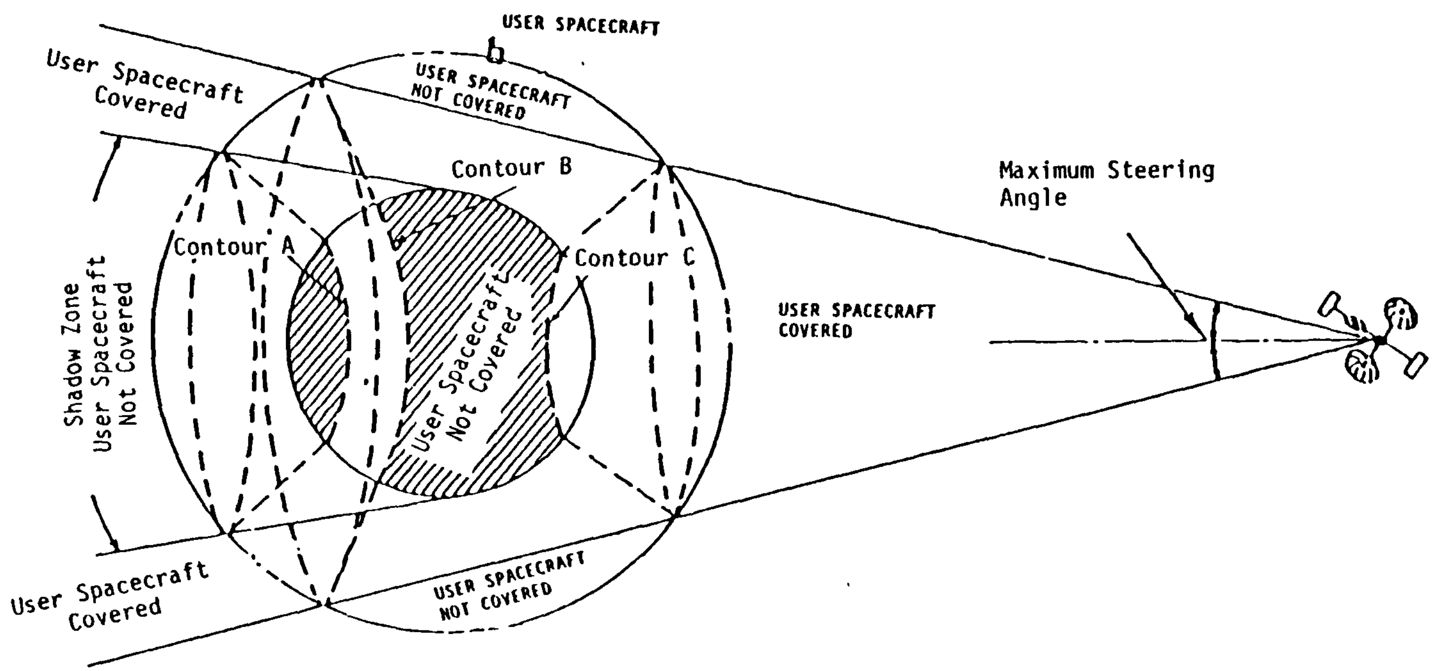


Figure 2-6
TDRSS Spatial Coverage Definition for Orbits Over 12,000 km.

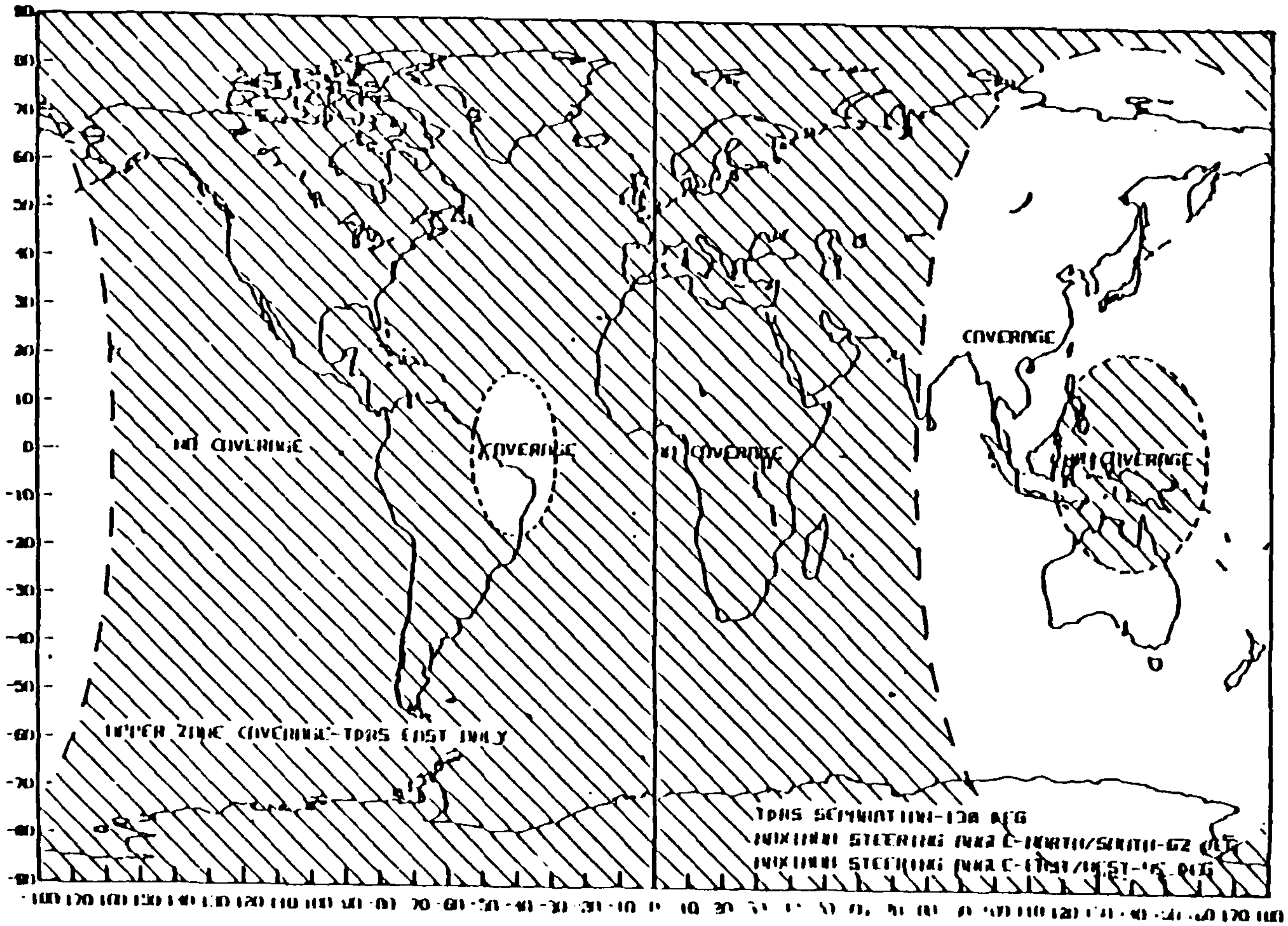


Figure 2-7
TDRS East Coverage for 20,000 km. Orbit

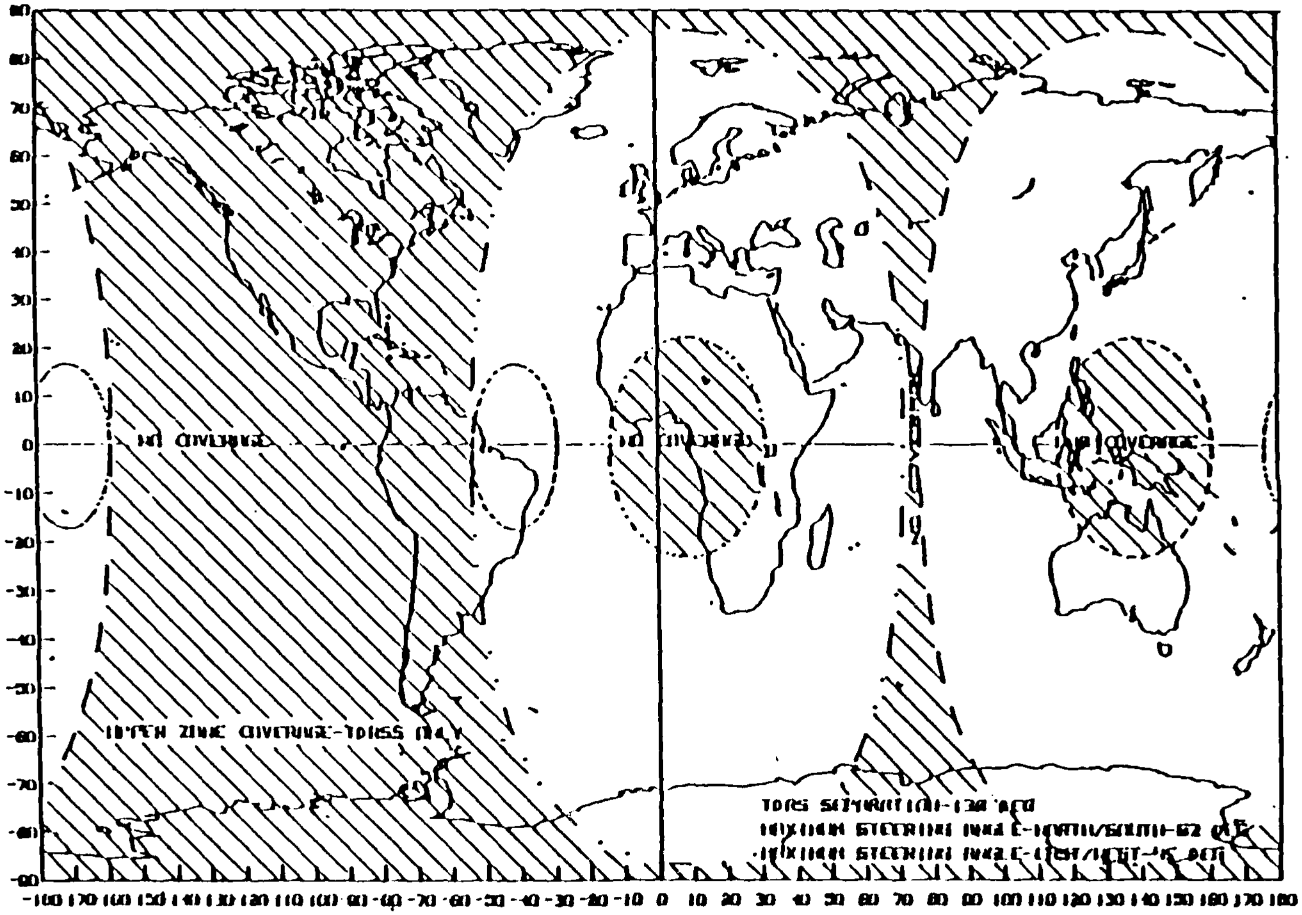


Figure 2-8
TDRS West Coverage for 20,000 km. Orbit

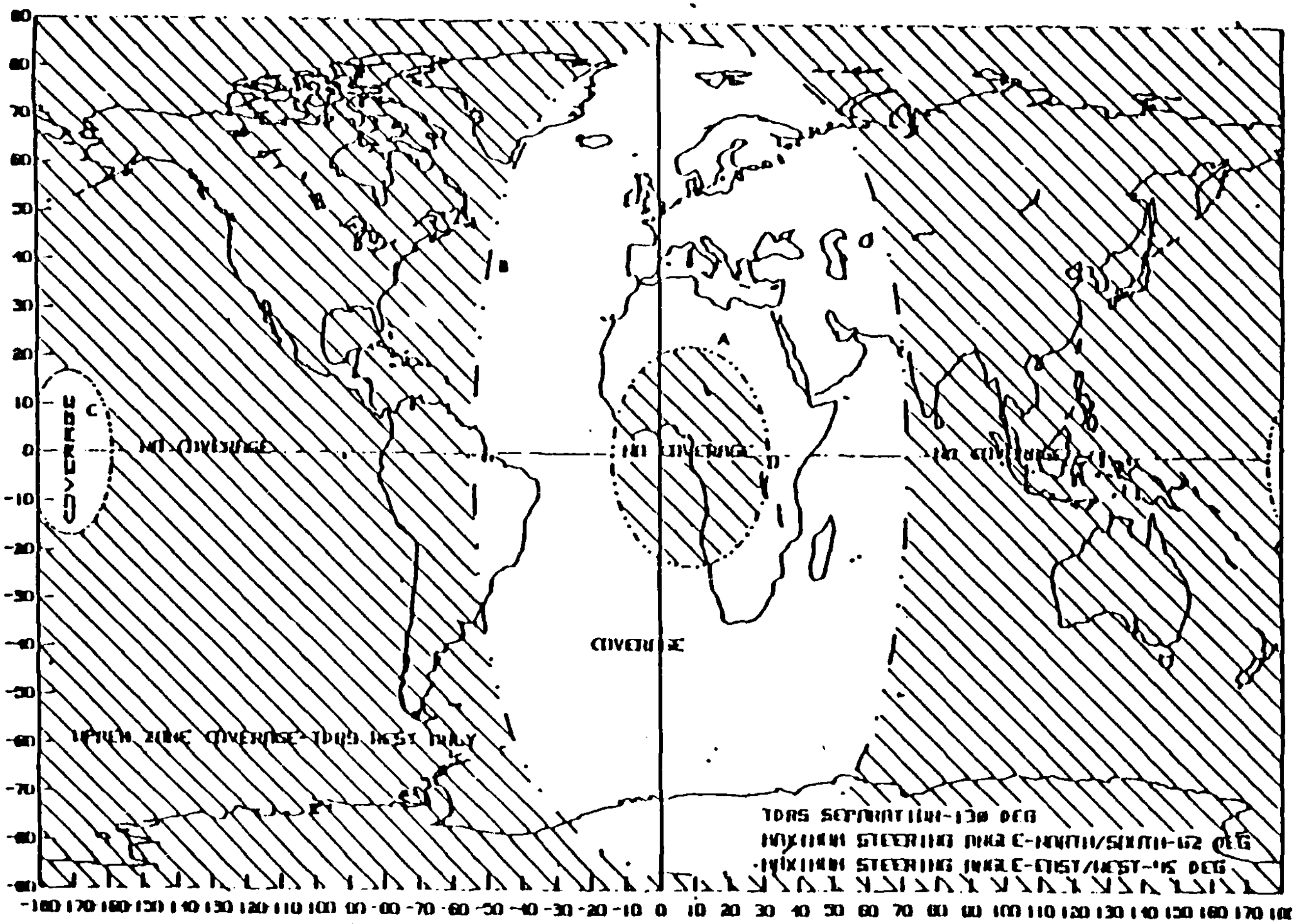


Figure 2-9
Complete TDRSS Coverage for 20,000 km. Orbit

- White Sands Ground Terminal (WSGT)
- NASA Ground Terminal (NGT)
- Network Control Center (NCC)
- NASA Communications Network (NASCOM)
- Operations Support Computing Facility (OSCF)
- NCC Fallback (NFB)

Figure 2-10 shows overall network interaction. [Ref. 2:p. 4-3]

1. White Sands Ground Terminal (WSGT)

Located at White Sands, New Mexico, WSGT provides message traffic carrying ground equipment and associated services which connect the NASA user traffic interface and the orbiting TDRS's. In addition, the ground terminal monitors and maintains the space segment of the TDRSS Network.

Elements of the ground terminal consists of:

- Three 18.3 meter K-band user traffic antennas and an S-band telemetry and command (T&C) antenna for measurement of axial ratio. These include appropriate switching, multiplexing, and control center equipment.
- Colocated operations building with associated RF signal processing, data processing, and control center equipment.
- Calibration, simulation and verification equipment.
- NASA communications, control, and user equipment.

WSGT is divided into ten major subsystems as shown in Figure 2-11. The antenna and RF subsystems provide the ground RF interface with the space segment. The data subsystem has four components: system control and computing; user link equipment for spacecraft range and doppler measurements and signal decoding; telemetry, tracking and command (TT&C) devices for the TDRSs; and the Multiple Access component consisting of convolutional decoders that simultaneously process bit streams of up to 20 MA user spacecraft. [Ref. 3:pp. 50-60]

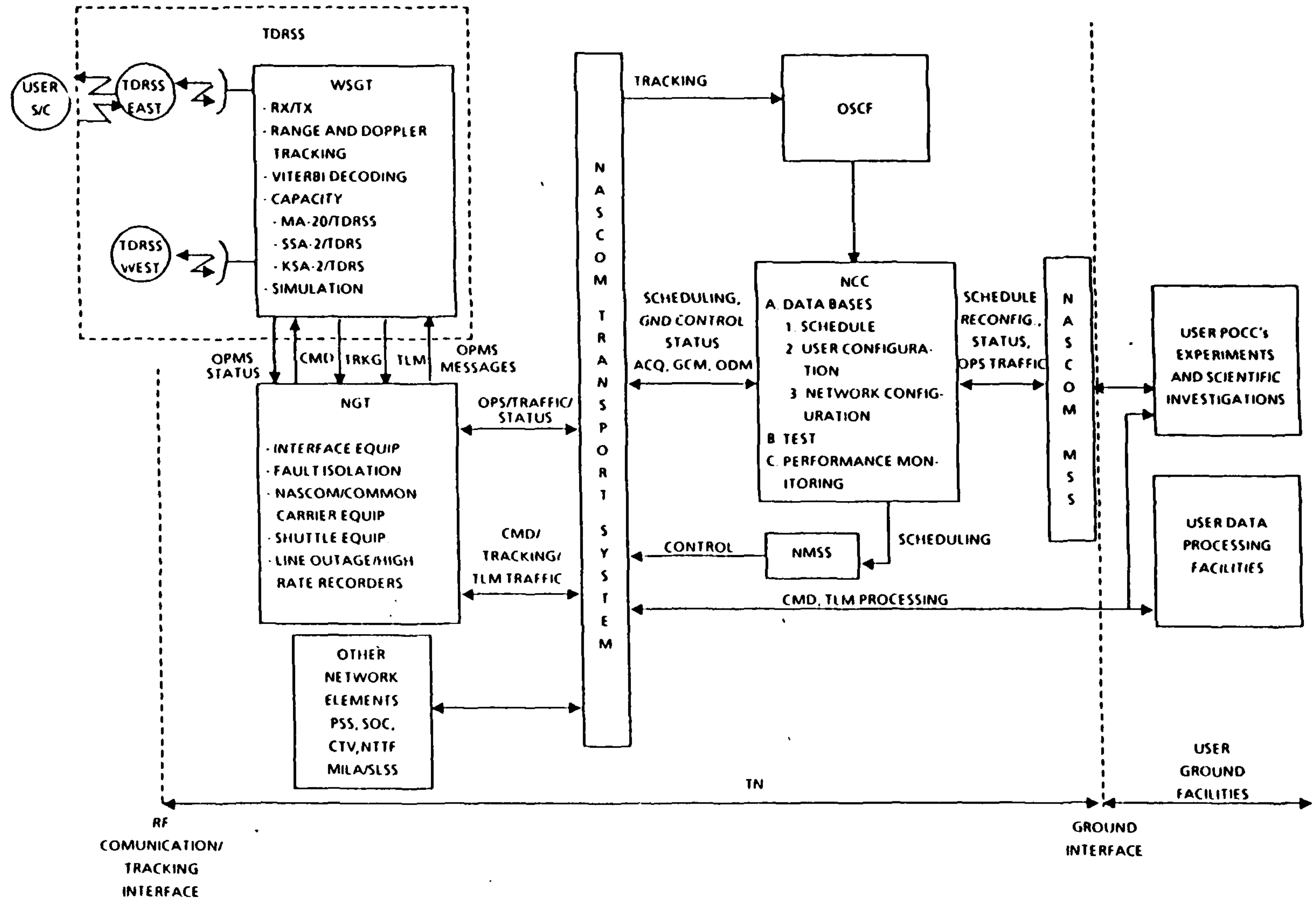


Figure 2-10
TDRSS Network Interface

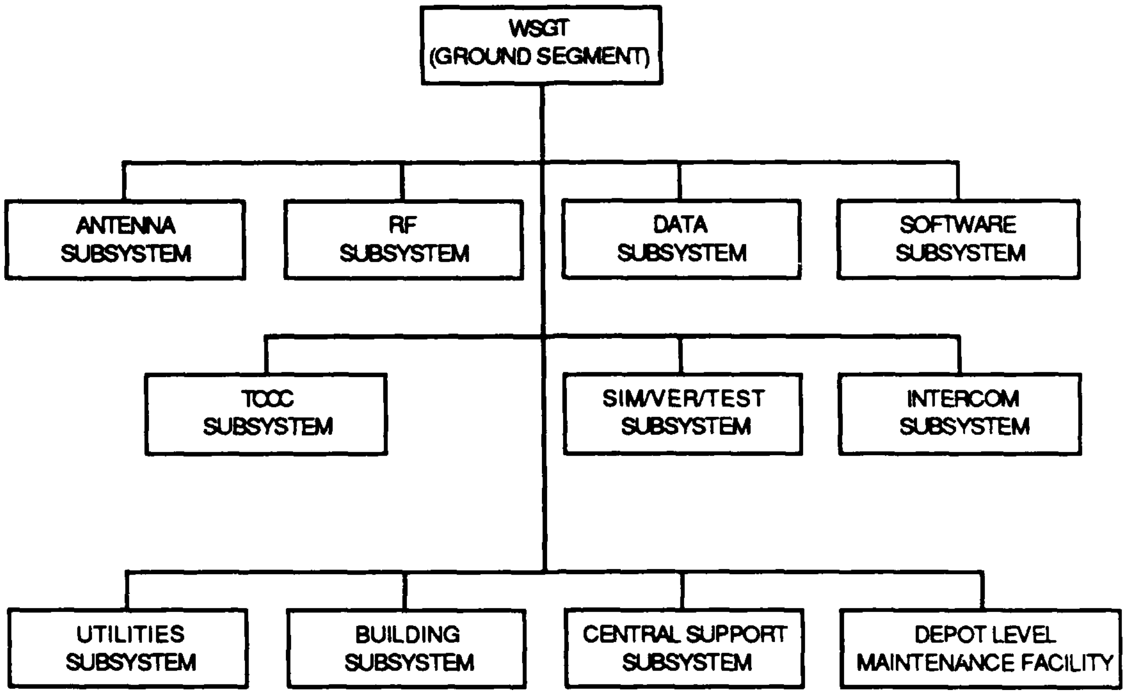


Figure 2-11
WSGT Organization

The software subsystem includes all software used operationally in all processors in the data subsystem. This supports ground segment equipment configuration control and monitoring, tracking calculations, TDRS antenna pointing, calibration, reporting of TDRSS status to NASA, and scheduling of TDRSS resources.

Simulations/verifications subsystem supports the corresponding simulations/verification user service. It also provides an internal test capability for TDRSS fault isolation. Finally, the TDRSS Operations Control Center (TOCC) provides the principal man/machine interface for control of TDRSS.

In order to reduce the complexity of the space segment and allow technical adaptability, many normally spaceborne functions of the system are performed on

the ground. This accounts for the complexity of the ground functions, but also locates critical activities to easy access for repair and modification.

2. NASA Ground Terminal (NGT)

Colocated with WSGT, the NGT is the interface for communications between the TDRSS WSGT and remote user elements and NASA facilities. The NGT is a terminal point in the multilink path of communications between user spacecraft and user POCC's.

All digital and analog communications between TDRSS and the remainder of the network pass through NGT. This interface function includes multiplexing/demultiplexing, buffering, switching, and circuit selection. Additionally, NGT provides network controlling interface for tracking data sent from the WSGT to the OSCF. Finally, the NGT monitors system forward and return data channels to assist the NCC in fault isolation operations and TDRSS performance evaluation.

As shown in Figure 2-12, NGT receives system control information from two sources, the NCC and the NASCOM control center at Goddard Space Flight Center (GSFC). The NASCOM control center controls and monitors those aspects of the NGT throughput functions that require coordination with the NASCOM supplied circuit terminations at GSFC and Johnson Space Center (JSC). The NASCOM control center, in turn, receives its direction from the NCC. The NCC directly controls and monitors the NGT function of data link monitoring, line outage protection, and data rate buffering.

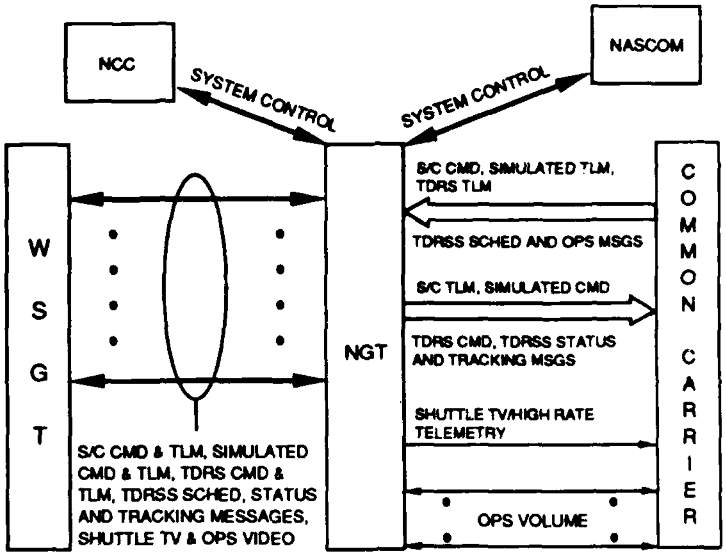


Figure 2-12
NGT Control Process

3. Network Control Center (NCC)

The NCC at GSFC, Greenbelt, Maryland, provides overall management, control, and accounting of NASA access to TDRSS communications services. This includes advance scheduling of user support periods, implementing the schedule by digital messages, and acting as a real time control interface to users.

All user spacecraft operations supported by the TDRSS Network are scheduled by the NCC. User POCC's can start requesting support up to 21 days prior to a user event. The schedule request must indicate the type of service, duration, and acceptable support time. From the complete spectrum of user requests, the NCC prepares a master schedule of all TDRSS, NASCOM, and NGT support activities needed. The schedule is kept current as users' needs change but is finalized at least 24 hours prior to support time. In the event of an emergency event, NCC can provide a response time of 10 minutes or less.

4. NASA Communications Network (NASCOM)

The NASCOM is the umbrella system tying most of the other elements together. It provides a baseline and a high data rate transport system connecting NGT, GSFC, and JSC. Across these circuits pass user forward and return data, system status and control, and other NASA housekeeping functions. Baseline services include a 1.544 Mb/sec link in the forward direction and 4 Mb/sec in the return direction. User ground facility operations normally access the TDRSS through the JSC and GSFC for transportation of their spacecraft command control, telemetry, and low data rate science data. By leasing two common carrier Domestic Satellite (DOMSAT) services, NASCOM connects JSC and GSFC with NGT at White Sands (Figure 2-13). With redundancy along paths, much greater system reliability can be assured during periods of DOMSAT or terminal outage.

For delivery of high data rate science and image data to user ground facilities, the baseline system is augmented by more specialized DOMSAT communications services. This high data rate return traffic can consist of one of the following: 48 Mb/sec; a standard commercial television signal; or a 20 Hz to 4.2 MHz analog bandwidth channel.

In addition, NASCOM provides high speed teletype from GSFC to the NGT and JSC for transmission of NCC high speed NASCOM scheduling and control messages. It also provides an interconnect for NCC through the baseline system with NGT, which in turn is locally interconnected with WSGT.

5. Operations Support Computing Facility (OSCF)

Located at GSFC, the OSCF is the primary facility for orbit and orbit related computational support for the TDRSs' and user spacecraft. The OSCF

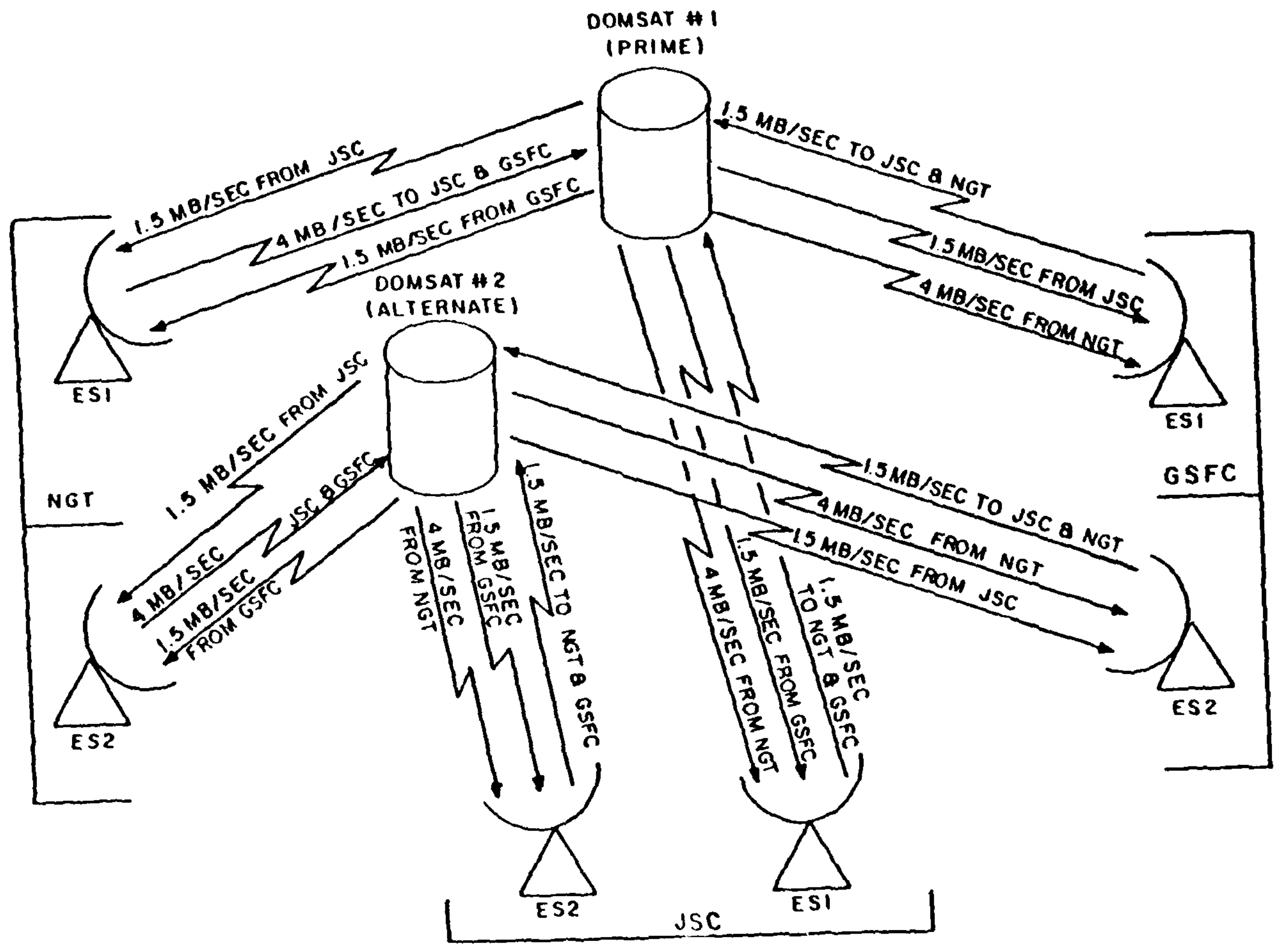


Figure 2-13
Prime and Alternate Trinodal Broadcast Configuration for the NASCOM Data Transport System

receives, processes, and recorc metric tracking data to provide orbit determination and computations for developing trajectory information and for acquisition data and scheduling aids.

The OSCF receives its tracking data through NASCOM from WSGT. Comparisons are made between actual and predicted user spacecraft position. Updated acquisition data is then generated and Predicted Site Acquisition Tables defining periods of mutual visibility between user spacecraft and each TDRS are provided to the NCC and user POCC's. State vectors and force models are then forwarded to WSGT for important determination of TDRS antenna look angles.

6. NCC Fallback (NFB)

The NFB at GSFC performs the network management functions for scheduling and allocating resources to meet mission requirements in the event of a major NCC failure. The NFB is physically separated from the NCC and contains most of the NCC control capabilities; however, some are manual versus automated implementations. Operations in this mode will degrade overall system response to a negligible degree.

III. TDRSS COMMUNICATIONS TECHNICAL PARAMETERS

A. INTRODUCTION

The user has a two point interface with the TDRSS Network: the ground segment interface at either JSC or GSFC and between the user spacecraft and TDRSS spaceborne assets. Both of these interfaces require exacting design and specificity, but the limiting factor in terms of link quality is the space link. All space link calculations are based on a bit error rate (BER) of 10^{-5}, as provided by NASA. On the other hand, the ground segment link is limited by the NASCOM achievable BER of 10^{-7}. For this reason the contents of this chapter will be devoted to presenting the technical requirements and performance of the space interface.

B. TDRSS TELECOMMUNICATIONS SERVICES

Because the familiar terms uplink and downlink are not operative in this system, forward and return links to and from the user spacecraft and the TDRS's will be the nomenclature used throughout this discussion. The conventional uplink and downlink between WSGT and each TDRS is virtually transparent to the user due to much greater antenna gains available. Hence the governing elements of the TDRSS are the parameters of the forward and return links up to the design level of quality of 10^{-5}.

These forward and return links have very specific constraints as to implementation which define the internal receiver data stream generation and preparation. Off-the-shelf hardware is available but users may decide to design and construct their own with possible cost and weight savings. Available modes of service are the following:

- Multiple Access (MA) Service
- Single Access (SA) Service
- Tracking Service

Figures 3-1 and 3-2 depict the overall frequency plans for forward link service and return link service respectively. [Ref. 4:pp. 11-12]

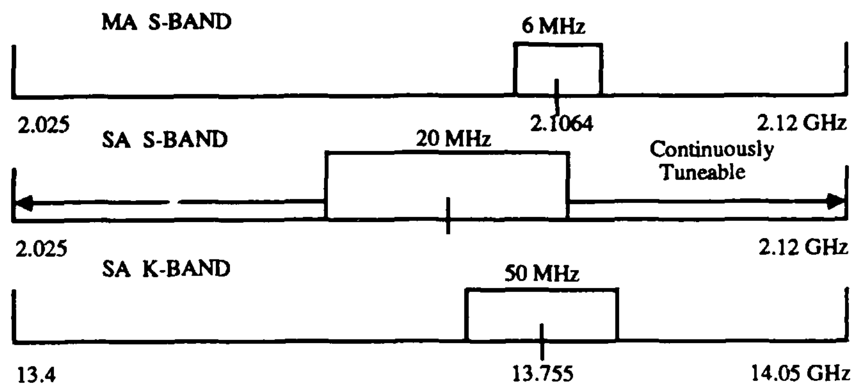


Figure 3-1. Forward Link Frequency Plan

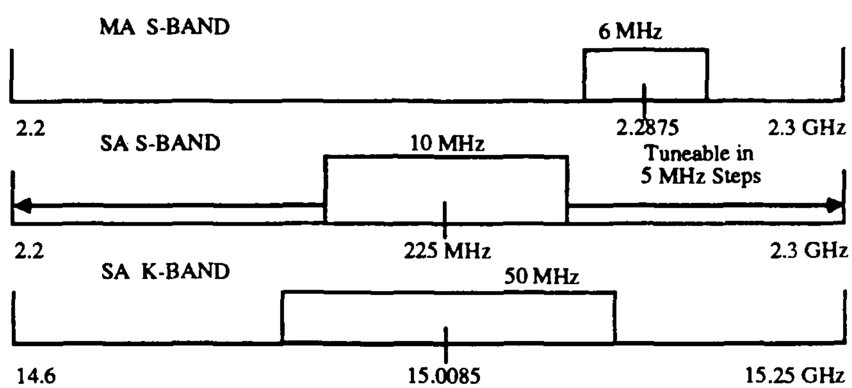


Figure 3-2. Return Link Frequency Plan

C. SIGNAL CHARACTERISTICS

1. Forward Service

All three of the forward service types (MA, SA, KSA) consist of a pseudo-random noise (PN) code modulated command channel in quadrature with a PN code modulated range channel. PN codes are extremely long binary sequences that possess very good autocorrelation properties. By modulating the signals with the codes the spectrum is spread substantially and appears as random noise. NASA provides these codes to the user SC as part of initial design. [Ref. 5]

Forward service data 300 kbs or less is modulo-2 added asynchronously to the command channel PN code for signal acquisition. The K-band SA forward link is the only service for command data greater than 300 kbs and its carrier is BPSK modulated without range channel transmission.

2. Return Service

Table 3-1 summarizes the signal design characteristics available for return service. Two signal designs designated Data Group 1 (DG1) and Data Group 2 (DG2) are available to return service users. DG1 is further subdivided into modes 1, 2, and 3.

D. MULTIPLE ACCESS (MA) SERVICE

MA service provides return capability to low earth orbiting user spacecraft for real time or playback data rates up to 50 kbs. Return service can support up to 20 user spacecraft simultaneously through the use of PN coding and beamforming. Beamforming is not performed at the TDRSs, but is computer synthesized at WSGT instead. Forward service is time shared among users with a maximum individual user spacecraft received data rate of 10 kbs for one user per TDRS at a time.

TABLE 3-1. RETURN LINK SIGNAL CHARACTERISTICS

Characteristics	DG1 M1	DG1 M2	DG1 M3I	DG1 M3Q	DG2
SQPN[a]	YES	YES	YES	NO	NO
BPSK[b]	NO	NO	NO	YES	YES
QPSK[c]	NO	NO	NO	NO	YES
SQPSK[d]	NO	NO	NO	NO	YES
MOD-2 PN ASYNCH	YES	YES	YES	NO	NO
Coherent turnaround of forward carrier required	YES	NO	YES	YES	NO
Noncoherent carrier allowed	NO	YES	NO	NO	YES

[a] Staggered Quadriphase Pseudorandom Noise
[b] Biphase Shift Key
[c] Quadrature Phase Shift Key
[d] Staggered Quadriphase Shift Key

1. MA Forward Link

All TDRSS MA forward services incorporate spread spectrum modulation techniques. Prior to a service period, the user POCC must provide the center frequency, f_o, of the user spacecraft to the NCC. This data facilitates doppler compensation of the TDRS carrier so that the arriving signal will be within a predictable error tolerance of f_o. This feature minimizes doppler resolution requirements for the user spacecraft and aids in rapid reacquisition in the event of broken lock. It can be inhibited by WSGT at the request of the user POCC. The unique PN code chip rate is coherently related to the TDRS carrier frequency in all cases. With this feature, the user spacecraft can use the receiver PN code clock to predict the received carrier frequency. Separate but simultaneous command and range channels are provided in the forward service. The command channel

includes a rapidly acquirable PN code and contains the forward data. The range channel contains a PN code which facilitates range ambiguity resolution requirements. TDRSS MA forward service parameters are listed in Table 3-2. [Ref. 2:pp.3-7 - 3-14]

TABLE 3-2. MA FORWARD SERVICE PARAMETERS

Parameter	Description
Command Channel	
PN code length	$2^{10} - 1$
PN code type	Gold Code
PN code chip rate	$(31/(221 \times 96)) \times f_c$
Data Modulation	Modulo-2 added asynchronously to PN code
Data Format	NRZ
Data Rate Limits	.1 - 10 kbs
Range Channel	
PN code length	$(2^{10} - 1) \times 256$
PN code type	Truncated 18-stage SR
Forward Link (each TDRS)	
Field of View	± 13° Conical
Antenna Polarization	LHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
EIRP	+ 34 dBW
f_c	$(2287.5 \pm .1) \times 221/240$ MHz
RF Bandwidth	6 MHz

2. MA Return Link

A user spacecraft must use convolutional (Rate 1/2) encoding for all return service data and can only use DG1 modes 1 and 2 signal designs. Data signals on the I and Q channels may be independent and asynchronous. If the I and Q channel data signals are independent the sum of the data rates must not exceed 50 kbs. For single channel operation, the I and Q channels must be identical and synchronous and the data rate may not exceed 50 kbs. Power division ratio may be weighed to a

maximum of 4:1 in favor of the Q channel in either single or dual channel operation.

The I and Q channel PN codes are generated from a single unique code generator. For DG1 mode 1, the I and Q channel PN codes are identical but offset by at least 20,000 chips. For both modes the return data stream will be modulo-2 added asynchronously to the channel PN code. This eliminates the need for synchronizing the user spacecraft data clock with the PN code clock. The PN code clock, however, must be coherently related to the transmitted carrier frequency to permit WSGT to use the PN code clock to aid return service carrier acquisition.

DG1 mode 1 signal design must be utilized when two way range and doppler measurements are required. PN code length will be identical to that of the forward link range channel PN code received from the TDRS. This coherence of forward link carrier and PN code with the user spacecraft will be lost when the TDRS no longer is transmitting. In this event the user transmitter must switch to DG1 mode 2 noncoherent transmitter operation. In this mode the carrier frequency is defined by the user POCC to a tolerance of ± 700 Hz prior to service. TDRSS MA return service parameters are listed in Table 3-3. [Ref. 2:pp. 3-40 - 3-50]

E. S-BAND SINGLE ACCESS (SSA) SERVICE

Each TDRS can provide two SSA forward and return services for a total of four each for the TDRSS. This service is continually available for SSA users on a time shared basis. User spacecraft are discriminated by frequency, polarization, unique PN codes, and TDRS antenna beam pointing. The entire TDRSS can combine the signals received through both TDRSs from a user spacecraft to provide a nominal 2.5 dB increase in return performance.

TABLE 3-3. MA RETURN SERVICE PARAMETERS

Parameter	Description
Return Link	
Field of View	± 13° Conical
Antenna Polarization	LHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
Receive Freq. (nominal)	2287.5 ± .1 MHz
Signal Acquisition	
User Spacecraft Dynamics	$\ddot{R} \leq 15$ m/sec^2
P_{rec}	$\geq$ -188.2 dBW
Signal Tracking	
Spacecraft Dynamics	$\ddot{R} \leq 50$ m/sec^2
Maximum P_{rec}	-159.2 dBW
PN code chip rate	$(31/(240 \times 96)) \times f_c$
PN code length	
DG1 mode 1	$(2^{10} - 1) \times 256$
DG2 mode 2	$2^{11} - 1$
PN code types	
DG1 mode 1	Truncated 18-stage SR
DG1 mode 2	Gold code
Symbol Format	NRZ, Biϕ-L
Data Format	NRZ-L, NRZ-M, NRZ-S
Data Rate Restrictions	
DG1 mode 1	.1 - 50 kbs
DG1 mode 2	1-50 kbs

1. SSA Forward Link

All TDRSS SSA forward services use spread spectrum techniques to satisfy flux density limitations impinging at the earth's surface. Much like MA service, SSA can provide doppler compensation and has coherent relation between the PN code clock and carrier frequency. It also provides dual command and range channels for simultaneous data transmission of data and range tracking. The signal is an unbalanced QPSK modulation with an allowable command/range channel ratio of 10 dB. Table 3-4 summarizes the forward link parameters. [Ref. 2:pp. 3-40 - 3-50]

TABLE 3-4. SSA FORWARD SERVICE PARAMETERS

Parameter	Description
Command Channel	
PN code length	$2^{10} - 1$
PN code type	Gold Code
PN code chip rate	$(31/(221 \times 96)) \times f_c$
Data Modulation	Modulo-2 added asynchronously to PN code
Data Format	NRZ
Data Rate Limits	.1 - 300 kbs
Range Channel	
PN code length	$(2^{10} - 1) \times 256$
PN code type	Truncated 18-stage SR
Forward Link (each TDRS)	
Field of View	± 22.5° East-West ± 31° North-South
Antenna Polarization	Selectable LHC or RHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
EIRP	
Normal mode	± 43.6 dBW
High power	± 46.1 dBW
f_c	Selectable over (2200 - 2300) x 221/240 MHz
RF Bandwidth	20 MHz

2. SSA Return Link

Convolutional encoding (Rate 1/2 or 1/3) must be used for all user spacecraft SSA transmissions to minimize P_{rec} and as a RFI mitigation technique. SSA return service signals that are Rate 1/3 convolutionally encoded will incur the lowest RFI degradations. In addition, at symbol rates above 300 ks/sec, symbol interleaving of the user spacecraft transmission must be used.

All signal design options, DG1 modes 1, 2, and 3, and DG2, are available to the SSA user spacecraft. The DG1 mode 1 is used when two way range and doppler measurements are required simultaneously with data transmission. DG1 mode 2 is utilized when noncoherent transponder operation is permissible. DG1

mode 3 is similar to mode 1 except that the Q channel must contain only data and no PN code.

DG1 modes 1 and 2 can have either a single channel or two independent channels. The I and Q channel power division in the user spacecraft transmitter can be weighted to a maximum of 4:1 for the Q channel. DG1 mode 3 can be either single or dual as well, but, for a single channel, the data appears on the Q channel and only range tracking on the I channel.

In single channel operations, DG1 modes 1 and 2 data rates may not exceed 150 kbs. For dual channel, the sum may not exceed 300 kbs. Single channel DG1 mode 3 data rate is limited to 150 kbs for the I channel. In dual channel the I channel limit is 150 kbs and Q channel limit is 3 Mbs for a total of 3.15 Mbs.

DG2 signal parameters are used when return data rate requirements exceed DG1 capabilities. TDRSS range tracking is not provided due to the lack of PN modulation . Doppler two way tracking can be provided when the DG2 carrier is coherently related to TDRSS forward service. DG2 can have either single or dual data channel operation. For data rates ≤ 3 Mbs BPSK can be used for DG2 and must be used for data rates ≤ 50 kbs. The I channel data rate limit is 3 Mbs and Q channel is 150 kbs for total of 3.15 Mbs in dual channel operation. Table 3-5 summarizes SSA return service parameters. [Ref. 2:pp. 3-85 - 3-97]

F. K-BAND SINGLE ACCESS (KSA) SERVICE

Like SSA service, the TDRSs will each support two forward and two return KSA services for a total of four each in the TDRSS. These services are time shared among all the KSA users and user spacecraft are discriminated by polarization, unique PN codes, and TDRS antenna beampointing. KSA provides high data rate capability in both forward and return links.

Table 3-5. SSA Return Service Parameters

Parameter	Description
Return Link (TDRS)	
Field of View	± 22.5° East-West ± 31° North-South
Antenna Polarization	LHC or RHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
Receive Freq. Band	2200 - 2300 MHz
Signal Acquisition DG1	
User Spacecraft Dynamics	$\ddot{R} \leq 15 m/sec^2$
P_{rec}	
$T_{acq} \leq 15$ sec	$\geq$ -198.2 dBW
$T_{acq} \leq 5$ sec	$\geq$ -188.2 dBW
Signal Acquisition DG2	
User Spacecraft Dynamics	$\ddot{R} \leq 50 m/sec^2$
P_{rec} for $T_{acq} \leq 5$ sec	$\geq$ -188.2 dBW
Maximum P_{rec}	$\leq$ 147.2 dBW
PN code chip rate	
DG1 mode 1,2, & 3	(31/(240x96)) x f_c
PN code length	
DG1 mode 1 & 3	(210 - 1) x 256
DG1 mode 2	2^{11} - 1
PN code type	
DG1 mode 1 & 3	Truncated 18-stage SR
DG1 mode 2	Gold Codes
DG1	
Data Modulation	
Mode 1, 2 & 3I	Modulo-2 added asynchoronously to PN code
Mode 3Q	PSK ± π/2
Data Format	NRZ-L, NRZ-M, NRZ-S
Symbol Format	NRZ, Biϕ-L
Mode 1 & 2 Data Rate Limits	.1 (1 M2) - 300 kbs
I Channel	.1 (1 M2) - 150 kbs
Q Channel	.1 (1 M2) - 150 kbs
Mode 3	.1 kbs - 3.15 Mbs
I Channel	.1 - 150 kbs
Q Channel	1 kbs - 3 Mbs
DG2	
Data Modulation	SQPSK, BPSK, QPSK
Data Format	NRZ-L, NRZ-M, NRZ-S
Symbol Format	NRZ, Biϕ-L
Data Rate Limits	1 kbs - 3.15 Mbs
I Channel	1 kbs - 3 Mbs
Q Channel	1 - 150 kbs
f_c	
DG1 Mode 1 & 3	Forward f_c x (240/221)
Mode 2	Local Oscillator
DG2	Either of above

1. KSA Forward Link

KSA forward service signal parameters are of similar construct to both MA and SSA with only nominally different values. One operational exception is that, due to the narrow beamwidth of the TDRS antenna, the TDRS must begin K-band autotrack of the user spacecraft before providing normal or high power service to the user. Due to flux density restrictions, service is out while the user spacecraft is within .5° of the earth's horizon as seen be the TDRS. Table 3-6 summarizes KSA forward service parameters. [Ref. 2:pp. 3-15 - 3-82]

Table 3-6. KSA Forward Service Parameters

Parameter	Description
Command Channel	
PN code length	$2^{10} - 1$
PN code type	Gold Code
PN code chip rate	$(31/(1469 \times 96)) \times f_c$
Data Modulation	Modulo-2 added asynchronously to PN code
Data Format	NRZ
Data Rate Limit	1 kbs - 25Mbs
Range Channel	
PN code length	$(2^{10} - 1) \times 256$
PN code type	Truncated 18-stage SR
Forward Link (TDRS)	
Field of View	± 22.5° East-West ± 31° North-South
Antenna Polarization	Selectable LHC or RHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
EIRP	
Normal Mode	+46.5 dBW
High Power	+48.5 dBW
Acquisition	+40 dBW
f_c	13.775 GHz ± 0.7 MHz
RF Bandwidth	50 MHz

2. KSA Return Service

User spacecraft can utilize either uncoded or Rate 1/2 convolutionally encoded data for KSA return service. DG1 modes 1, 2, and 3 and DG2 signal designs are available for user spacecraft. For DG1 modes 1 and 2, data rate maximums are double that for SSA service to 300 kbs single channel and 600 kbs for total service. For DG1 mode 3, the I channel data rate maximum is 300 kbs and Q channel maximum of 150 Mbs.

DG2 channel capacities are 150 Mbs each for a total of 300 Mbs. This signal design is used when data requirements exceed the capability of DG1 modes. DG2 carrier frequency can be either coherent or noncoherent with the forward carrier. Table 3-7 summarizes return service parameters. [Ref. 2:pp.3-97 - 3-131]

Table 3-7 KSA Return Service Parameters

Parameter	Description
Return Link (TDRS)	
Field of View	± 22.5° East-West ± 31° North-South
Antenna Polarization	LHC or RHC
Antenna Axial Ratio	1.5 dB over 3 dB beamwidth
Receive Frequency	(1600/1469) x 13.775 GHz ±.7MHz
Autotrack Acquistion	
User Spacecraft Dynamics	$\ddot{R} \leq 50$ m/sec^2
P_{rec} for $T_{acq} \leq 30$ sec	≥ -179.2 dBW
Max AngularVelocity	≤ .0135 deg/sec
Signal Acquisition DG1	
Spacecraft Dynamics	$\ddot{R} \leq 15$m/sec^2
P_{rec} for $T_{acq} \leq 5$ sec	≥ -179.2 dBW
Signal Acquisition DG2	
Spacecraft Dynamics	≤ 15m/sec^2
P_{rec} for $T_{acq} \leq 5$ sec	≥ -179.2 dBW
Minimum 3 dB Bandwidth Prior to Power Amp	DG1: ≥ 4.5 MHz or 2 x max symbol rate whichever greater DG2: ≥ 2 x max channel symbol rate
Max P_{rec}	-149.2 dBW
DG1	
PN code parameters	Same as SSA
Data Format	
w/o encoding	NRZ-L, NRZ-M, NRZ-S, Biφ-L, Biφ-M, Biφ-S
w/encoding	NRZ-L, NRZ-M, NRZ-S
DG2	
PN code	None
Data Format	Same as DG1

IV: USER SPACECRAFT ORBIT CONSIDERATIONS

A. INTRODUCTION

Mission driven orbit selection can have significant impacts on the feasibility of interfacing with the TDRSS Network. Principal effects dependent on orbit selection are ranges of the forward and return links, mutual acceleration between user spacecraft and each TDRS, and viewing opportunities for each TDRS over important segments of the mission profile.

Ranges between the user spacecraft and the TDRSs directly affect the viability of the link by increasing space path loss for a given frequency. Depending on available EIRP, the user spacecraft can be impacted in one of two ways for a given BER; either the transmit and receive locations must be restricted or the data rate must be set low enough to fit the greatest distance. A variation on the latter is to provide a means for varying data flow from the best to worst case.

In the preceding chapter, limits were listed for mutual acceleration in the return links for all services. These limits allow the TDRS to accommodate electronic matching of its carrier frequency to Doppler shifted received signals for successful acquisition and tracking. Examination of planned orbital dynamics can identify regions, if any, that fail compliance.

Orbit selection will impact viewing opportunities for each TDRS due to orbit altitude and inclination. Because TDRSS is a limited asset, careful plans must be made by competing user spacecraft controllers to maximize system use through proper scheduling. Over the course of orbits that determine a mission cycle, a timeline of each TDRS, both TDRSs, and periods of obscuration should be

established. With this in hand, spacecraft planners can extrapolate mission needs and determine if available TDRSS time can fill them.

B. BASIC ORBITAL MECHANICS

A brief review of orbital mechanics is in order to establish relationships and useful constants for use in later analysis. This report is concerned with circular (eccentricity=0) low earth orbits (LEO), that range from 200 to 1500 kilometers. The following apply: [Ref. 6:pp. 60-67]

$$\text{Radius of orbit: } r_o = r_E + h \text{ (km)} \qquad (4.1)$$

where: $r_E = 6.378 \times 10^3$ km

h= user orbital altitude (km)

Earth gravitational constant:

$$\mu_E = GM = 3.986 \times 10^5 \text{ km}^3/\text{sec}^2$$

where: G= universal gravitational constant

M= mass of earth

Satellite mean angular velocity:

$$n = (\mu_E / r_o^3)^{\frac{1}{2}} \text{ (rad/sec)} \qquad (4.2)$$

Orbital period:

$$P = 2\pi/n \text{ (sec)} \qquad (4.3)$$

Radius of geosynchronous orbit:

$$\text{GEO} = 42164 \text{ km}$$

Since each TDRS is geostationary, it remains fixed relative to an earth bound position. However, due to both the earth's rotation and perturbation forces, the user spacecraft track will continuously shift relative to each TDRS. Viewing the orbit from above the plane of orbit, the spacecraft position can be viewed as a rotating unit vector in the x-y plane. The rotating vector can be expressed as and is a function of elapsed time and the orbital angular velocity n.

$$\vec{R}_1 = \cos(nt)\,\hat{i} + \sin(nt)\,\hat{j} \qquad (4.4)$$

To account for inclination (I) of the orbital plane from a stationary geocentric x-y reference plane, a transformation of axes must be performed for a rotation about the x axis. This yields a new set of equations defining R2:

$$\vec{R}_2 = \cos(nt)\,\hat{i} + \cos(I)\sin(nt)\,\hat{j} + \sin(I)\sin(nt)\,\hat{k} \qquad (4.5)$$

These conditions are for a perfectly spherical earth with no outside perturbations and that does not rotate. Each of these, to varying degrees, cause a distortion of the orbital path to a fixed observer on the earth or, like a TDRS, fixed relative to the earth coordinates. Accounting for earth rotation requires another transformation of axes for earth rotation about the z axis. From this comes

$$\vec{R} = x\,\hat{i} + y\,\hat{j} + z\,\hat{k} \qquad (4.6)$$

where $x = \cos(\partial t)\cos(nt) + \sin(\partial t)\cos(I)\sin(nt)$

$y = -\sin(\partial t)\cos(nt) + \cos(\partial t)\cos(I)\sin(nt)$

$z = \sin(I)\sin(nt)$

$\partial =$ earth angular velocity $= 7.27 \times 10^{-5}$ rad/sec

With slight adjustment for precession, this equation is sufficient for preliminary planning for prospective TDRSS users. To get polar coordinates in terms of earth latitude and longitude, use Figure 4-1. Depending on starting time and initial coordinates, latitude Φ and latitude Θ can be calculated as a function of time. The other significant values, n and I, depend on orbit selection.

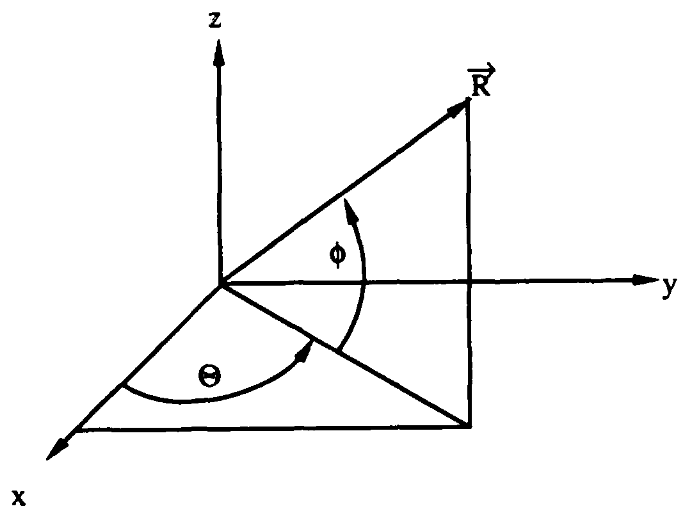


Figure 4-1
Latitude and Longitude Relationship

For any given time, t, both angles can be described as

$$\text{latitude } \Phi = \sin^{-1}[\sin(I)\sin(nt)] \qquad (4.7)$$

and

$$\text{longitude } \Theta = \tan^{-1}(y/x)$$

$$= \tan^{-1}\left[\frac{-\sin(\delta t)\cos(nt) + \cos(\delta t)\cos(I)\sin(nt)}{\cos(\delta t)\cos(nt) + \sin(\delta t)\cos(I)\sin(nt)}\right] \qquad (4.8)$$

C. RANGE DETERMINATION

Since this report deals with presumably low power capacity spacecraft, range determination becomes very important for evaluating the viability of a TDRSS link. Rather than solve a lengthy quadratic involving the equations of the last section, the best and worst case scenarios can be presented. Figure 4-2 shows the alignment which will yield both cases in the same orbit. In this case the ascending

(or descending) node of the satellite is the sub-satellite point of the TDRS. This is the shortest range possible in the orbit. The worst case range will remain the same

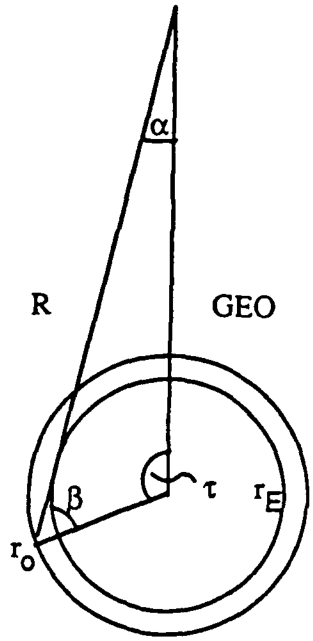


Figure 4-2 Maximum and Minimum Range

whatever the orbit orientation. The following relationships exist:

$$\alpha = \sin^{-1}(r_E/GEO) = 8.7° \quad (4.9)$$

$$ß = \sin^{-1}(r_E/r_o) \quad (4.10)$$

$$\tau = 180-\alpha-ß \quad 4.11)$$

$$R_{min} = GEO-r_o \quad (4.12)$$

$$R_{max} = \frac{\sin(\tau)\ GEO\ r_o}{r_E} \quad (4.13)$$

For example, let r_o= 1500 km

then α= 8.7°; ß= 54.06°; τ= 117.24°

R_{max}= 46303 km R_{min}= 34286 km

For a given set of communications parameters, this translates to a performance difference of about 2.5 dB over the link. If more precise figures are needed, then the planner is referred to Appendix A for a detailed computer program that will evaluate range over the specified life of the orbit as a function of orbit time. This includes both rotational and perturbing effects in the analysis. Only in the most power critical situations does this variance of performance appear to warrant great concern.

D. ACCELERATION

Spacecraft planners must evaluate the mutual accelerations between their spacecraft and each TDRS to ensure acquisition and tracking requirements are met. Each possible orbit will introduce inherent accelerations for consideration. However, rather than differentiate the complex range equation resulting from use of equations 4.7 and 4.8, the worst case scenario follows from the same reasoning used in the previous section. Using plane geometry instead of spherical and making nt equivalent to τ then the following applies

$$R(t)= ((GEO-r_o\sin (nt))^2 + r_o^2 \cos^2 (nt))^{1/2} \qquad (4.14)$$

$$=(GEO^2 - 2r_o \sin (nt) + r_o^2)^{1/2} \qquad (4.15)$$

where GEO and r_o are expressed in meters. Differentiating twice for acceleration yields

$$\ddot{R} = \frac{n^2\, GEO\, r_o\, ((GEO^2 + r_o^2) \sin(nt) - GEO\, r_o(\sin^2(nt) + 1))}{(GEO^2 - 2\, GEO\, r_o \sin (nt) + r_o^2)^{3/2}} \qquad (4.16)$$

Evaluation of this equation for the selected LEO circular orbits yields values within the previously stated limits. However, these values must be added to those experienced during maneuvering to arrive at the cumulative affects. Elliptical orbits could be expected to have much more dramatic values than those for

circular. Table 4-1 shows a tabulation of maximum acceleration values for selected altitudes.

TABLE 4-1: SELECTED MAXIMUM ACCELERATIONS

Orbit Altitude (km)	A (m/sec^2)
100	11.22
200	10.91
300	10.62
400	10.34
500	10.07
600	9.81
700	9.56
800	9.32
900	9.09
1000	8.88
1100	8.66
1200	8.46
1300	8.27
1400	8.08
1500	7.89

E. TDRS AVAILABILITY

Figure 4-3 shows various average coverages as a function of altitude and inclinations. [Ref. 2:p. 2-8] The mission defines the specific coverage needed. For instance, an imaging system would always suffer the same zone of exclusion in geographic coverage. For that mission it may not be acceptable. Other missions, though, may not be strictly geographically dependent and need to evaluate the availability of the TDRSs separately over the life of the mission. Cases where this can become critical is during periods of saturation of TDRSS loading when mission planners must schedule their activity accordingly.

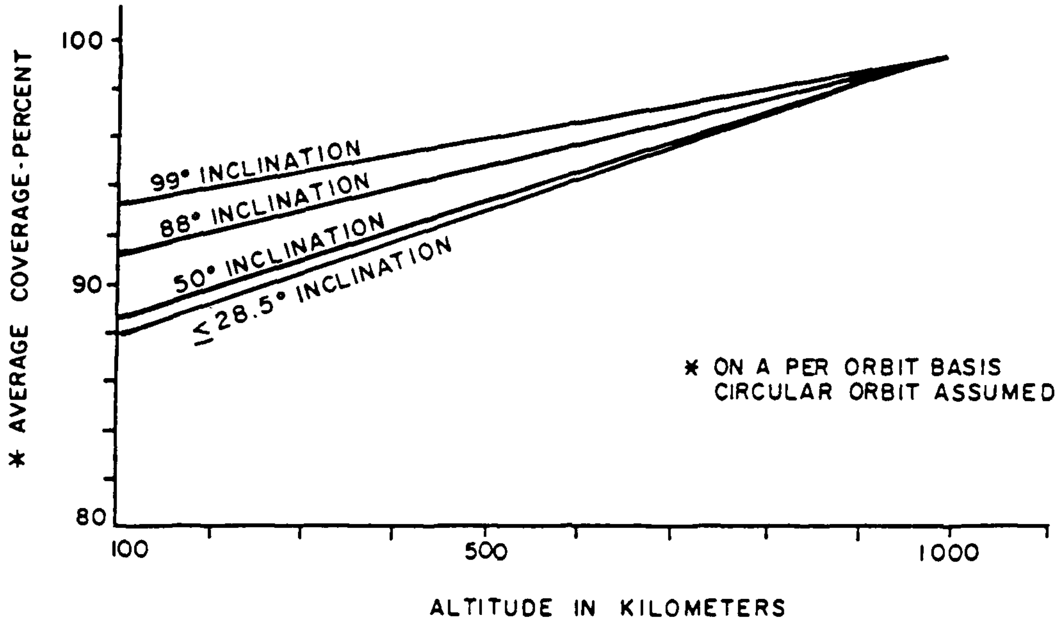


Figure 4-3

Average Geometric Coverage Versus User Spacecraft Altitudes at Various Inclinations

Appendix B is a program written to show TDRS viewing availability over a user designed span of orbits. It was adapted from Reference 7 methodology to assess TDRSS suitability for LANDSAT missions. Using this program in the planning stages of a particular mission can quickly check the coverage requirements against what can be provided. It will also define times and regions where alternative coverage means will be necessary. Actual implementation will require a much more precise model, but NASA has the support facilities in place to accomplish this.

Table 4-2 contains an example of this program for an orbital altitude of 300 kilometers at 30° inclination. Notice the nine minute gap in coverage for this one orbit and also a fourteen minute period of dual coverage.

TABLE 4-2 : AVAILABILITY PROGRAM EXAMPLE

TDRS AVAILABILITY AS A FUNCTION OF SATELLITE ORBIT

ORBITAL PARAMETERS USED

ORBIT ALTITUDE= 300 KM

ORBIT INCLINATION= 30 DEGREES

NUMBER OF ORBITS= 1

TDRS EAST LONGITUDE= -41.00 DEGREES

TDRS WEST LONGITUDE= -171.00 DEGREES

ORBIT PERIOD= 90.52 MINUTES

ORBIT NO.	DAY-HR-MIN			LAT	LONG	TDRS-E	TDRS-W
1	0	0	0	0.0	0.0	*	
1	0	0	5	8.9	14.6	*	
1	0	0	9	17.1	29.9	*	
1	0	0	14	23.9	46.6	*	
1	0	0	18	28.4	64.9		
1	0	0	23	30.0	84.3		
1	0	0	27	28.4	103.8		*
1	0	0	32	23.9	122.1		*
1	0	0	36	17.1	138.8		*
1	0	0	41	8.9	154.1		*
1	0	0	45	0.0	168.7		*
1	0	0	50	-8.9	183.3		*
1	0	0	54	-17.1	198.6		*
1	0	0	59	-23.9	215.3		*
1	0	1	3	-28.4	233.6	*	*
1	0	1	8	-30.0	253.0	*	*
1	0	1	12	-28.4	272.5	*	*
1	0	1	17	-23.9	290.8	*	
1	0	1	21	-17.1	307.5	*	
1	0	1	26	-8.9	322.8	*	
2	0	1	31	0.0	337.4	*	

V. LINK EVALUATION

A. INTRODUCTION

In any communications link, the designer wants to know if the mission can be accomplished within given constraints. In this context, the mission is the transfer of information of specified quality over the link. The performance for any link in the presence of additive Gaussian noise has been traditionally expressed in terms of a required signal-to-noise ratio (SNR) at some point in the receiver system. For an analog system, this will be taken at the output of the demodulator and serves as a figure of merit for the system. For digital links, like TDRSS, SNR is used to establish a bit error ratio (BER) at the output of the receiver.

All computational values and charts of Reference 2 are established for a TDRSS operation with a BER of 10^{-5}. Designers can, if they desire, use other values of BER up to the level at NASCOM of 10^{-7}. On the forward link the combined effects of a WSGT EIRP of 85+ dBW and an antenna gain on the TDRS of 44.5 dB make the noise contribution from this part of the link virtually transparent to the user SC. Likewise, the return link is affected little by the TDRS-WSGT link but to a greater extent than the forward. [Ref. 8:p. 4-53]

Forward link traffic requires no forward error correction as far as TDRSS is concerned, but users can code their own traffic without any effect on the operational requirements. All return traffic has forward error correction coding requirements except some of the KSA service modes. NASA has included the coding gains in the standard formulas and charts but only at a BER of 10^{-5}. User SC can utilize further error correction coding for higher quality links or to overcome

power deficiencies. This will require sacrificing some of the allowable data rate depending on the rate of the code.

B. DIGITAL DATA

Natural digital data are typically information such as commands, addresses, synchronization, words, or computer data. Derived digital data result from conversion of an analog voltage using pulse code modulation or delta modulation. No matter what voltage levels are assigned to represent the "zeros" and "ones", two distinct levels will be needed. Figure 5-1 shows the acceptable data formats for the TDRSS. It should be noted that the biphase formats will require approximately twice the bandwidth for a given data rate as the NRZ format.

The actual bandwidth required for transmission of a bit stream depends on the desired signal fidelity. A narrower transmission bandwidth results in more distorted pulses and corresponding performance loss.

In order to arrive at a probability of bit error (BER) for digital data links, the relation E_b/N_o needs to be computed. This is the bit energy-to-noise spectral density. [Ref. 9:p. 138]

$$\frac{E_b}{N_o} = \frac{ST_b}{N_o} \tag{5.1}$$

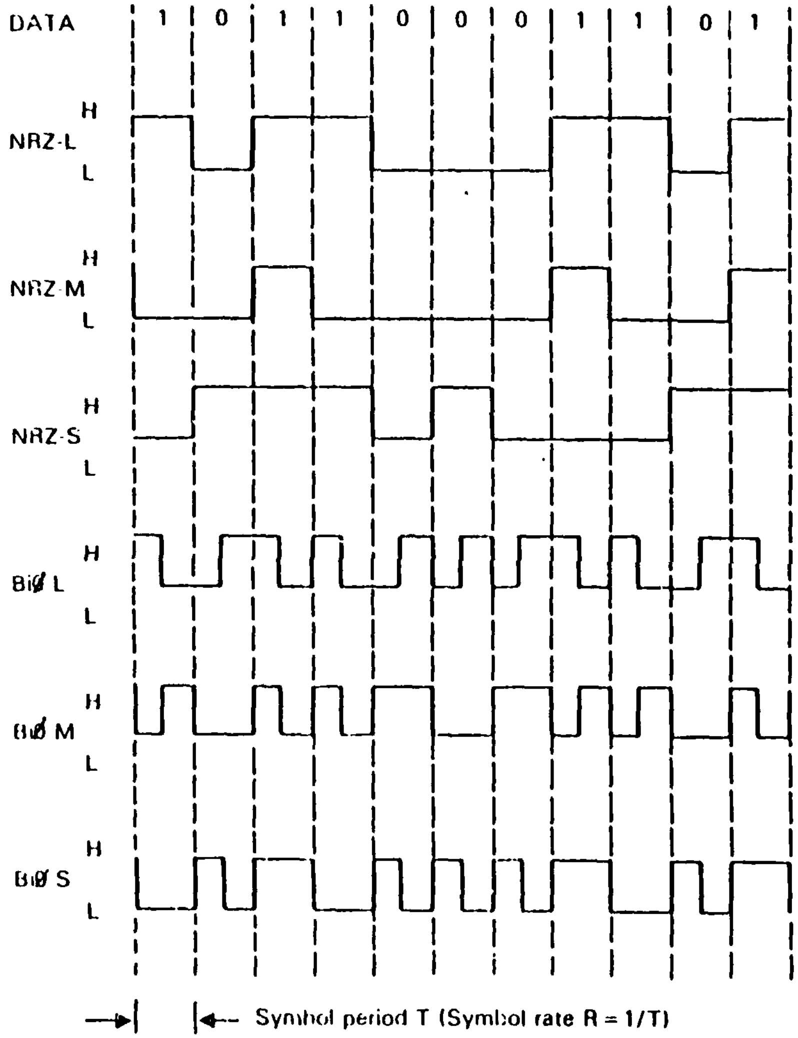
where

S = average signal power for the data channel.

T_b = bit duration time = $(\text{bit rate})^{-1} = \frac{1}{R_b}$

For error correcting coding such as that used in TDRSS, the total number of symbols increase and the values E_s, for energy per coded symbol, R_s, for symbol rate, and R for code rate (bit/symbol) are [Ref. 9:p. 139]

Symbol rate: $$R_s = R_b/R \tag{5.2}$$



Sequence of binary symbols (bits, chips) "1" and "0"

Non-Return-to-Zero-Level
"1" is represented by a high (H) level during the symbol period
"0" is represented by a low (L) level during the symbol period

Non-Return-to-Zero-Mark
"1" is represented by a change in level
"0" is represented by no change in level

Non-Return-to-Zero-Space
"1" is represented by no change in level
"0" is represented by a change in level

Bi-phase-L (Manchester II)
A transition occurs at the middle of every symbol period
"1" is represented by a midperiod transition from H to L
"0" is represented by a midperiod transition from L to H

Bi-phase-Mark
A transition occurs at the beginning of every symbol period
"1" is represented by a midperiod transition
"0" is represented by no midperiod transition

Bi-phase-Space
A transition occurs at the beginning of every symbol period
"1" is represented by no midperiod transition
"0" is represented by a midperiod transition

Figure 5-1
Allowable Digital Data Formats

Symbol duration: $T_s = 1/R_s = R/R_b = RT_b$ (5.3)

and

$$\frac{E_s}{N_o} = \frac{ST_s}{N_o} = \frac{SRT_b}{N_o} = \frac{RE_b}{N_o} \tag{5.4}$$

Since the output of the decoder is at R_b, the important parameter is still E_b/N_o. For binary phase shift keying (BPSK) and quadri-phase shift keying (QPSK) systems a BER is found from [Ref. 9:p. 239]

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{E_b/N_o}\right) \tag{5.5}$$

Figure 5-2 [Ref. 10:p. A-6-6] shows a set of probability of bit error curves for uncoded PSK and for a range of convolutional codes. Also shown are the effects of nesting the convolutional codes within an outside code. Note the coding gains, i.e., the difference between E_b/N_o for PSK and each of the coding methods for a given P_e.

C. FORWARD LINK

In the forward link, performance is expressed in terms of having a sufficient E_b/N_o at the user SC to achieve the desired link operating point plus a nominal design margin. For the link, the following equations apply: [Ref. 2:pp. A-1 - A-4]

$$P_{rec}/N_o = EIRP + L_s + L_p + L_\theta + (G/T) + G_c - 10\log k \tag{5.6}$$

where

P_{rec} is total received power at user SC

EIRP= minimum TDRS effective isotropic radiated power in the direction of the user SC (dBW)

L_s= space path loss (dB)

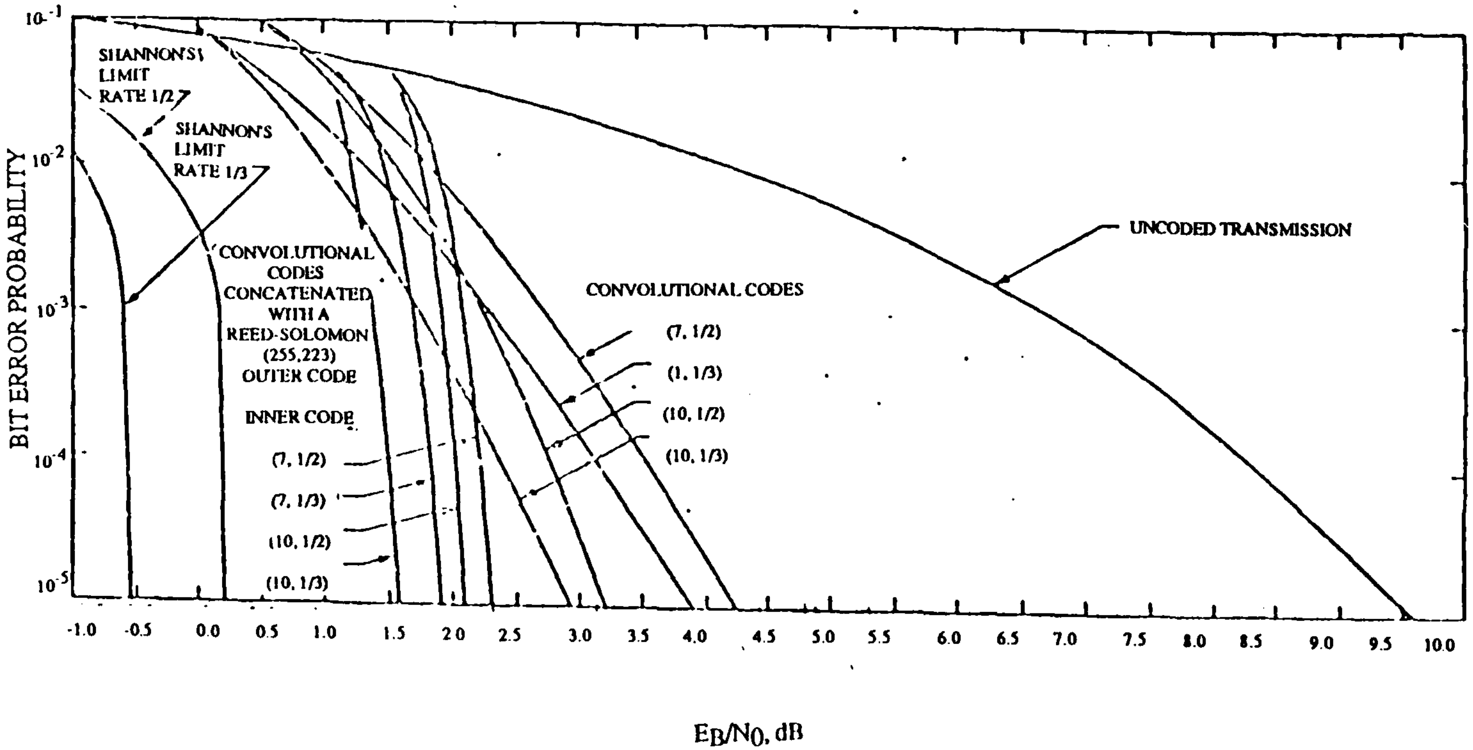


Figure 5-2
PSK Bit Error Probability Curves

$$L_s = -[\,32.45 + 20\log(R) + 20\log(f)] \qquad (5.7)$$

R is range of link in kilometers

f is TDRS transmission frequency in MHz

L_p = polarization mismatch loss (≤ 0 dB)

$$= 10\log\left[\frac{1}{2} + \frac{2R1R2}{(1+R1^2)(1+R2^2)} + \frac{(1-R1^2)(1-R2^2)\cos 2\phi}{2(1+R1^2)(1+R2_12)}\right] \qquad (5.8)$$

R1= axial ratio of transmit antenna

R2= axial ratio of receive antenna

ϕ= alignment angle between the two polarized ellipses

L_θ= antenna pointing losses (≤ 0 dB)

G/T= Antenna gain to equivalent noise temperature ratio of the user SC (dB/K)

G_c= coding gain (dB)

10logk= -228.6 dBW(Hz-K) (k= Boltzman constant)

and

$$E_b/N_o = P_{rec}/N_o - 10\log ADR + \gamma - M \qquad (5.9)$$

ADR= achievable data rate

γ= sum of user SC receiving system and TDRSS

forward service degradation, bit sync loss and distortion losses

M= desired operating margin

Combining equations 5.6 and 5.9, a new relationship can be established in terms of user SC G/T required to meet an achievable data rate (ADR) for a desired BER with other conditions constant.

$$G/T = 10\log ADR + 10\log k + E_b/N_o\,req + M - EIRP - L_s - L_p - L_\theta - G_c - \gamma \qquad (5.10)$$

where E_b/N_o req is the required value to meet a desired BER from Figure 5-2.

Since there are an infinite number of combined values for the variables in equation 5.10, Table 5-1 lists the nominal values which will be utilized in further analysis.

1. MA Forward Service

Using the values from Table 5-1, equations 5.10, and the MA EIRP of 34 dBW;

$$G/T = 10\log ADR + E_b/N_o\ req - G_c - 63.4 \qquad (5.11)$$

for circularly polarized user SC, and

$$G/T = 10\log ADR + E_b/N_o\ req - G_c - 60.9 \qquad (5.12)$$

for linearly polarized user SC.

TABLE 5-1 NOMINAL LINK EQUATION VALUES

L_s	= -192.7 dB	MA	(R_{max} at 1500 km. orbit)
	= -192.1 dB	SSA	(R_{max} and mid range f_c)
	= -208.5 dB	KSA	(R_{max})
L_p	= -.5 dB user SC circularly polarized		
	= -3.0 dB under SC linearly polarized		
L_Θ	= -.5 dB		
γ	= -2.5 dB		
M	= 3.0 dB		

E_b/N_o req (dB)	G_c R=1/2	G_c R=1/3	for BER
6.7	4.0	4.4	10^{-3}
8.4	4.8	5.3	10^{-4}
9.6	5.4	5.7	10^{-5}
10.4	5.6	6.0	10^{-6}
11.3	6.0	6.4	10^{-7}

With these equations, reference charts in Figures 5-3 and 5-4 are generated. Although uncoded graphs are illustrated for a BER of 10^{-3}, the user can easily arrive at other BER's by adding the difference between the two E_b/N_o req from Table 5-1 to the G/T value at the desired ADR. Notice the ADR ranges reduced by the coding rates to remain within the TDRSS channel.

2. SSA Forward Service

SSA forward service has two EIRP modes; normal at 43.6 dBW and high at 46.1 dBW. The high power mode is reserved for emergency conditions only and angular restrictions place most of the LEO's of this study out of its range anyway. Similar equations can be established

$$G/T = 10\log ADR + E_b/N_o\,req - G_c - 73.6 \tag{5.13}$$

for circular polarization and,

$$G/T = 10\log ADR + E_b/N_o\,req - G_c - 71.1 \tag{5.14}$$

for linear polarization. Figures 5-5 and 5-6 apply .

3. KSA Forward Service

Due to the extremely narrow beamwidth (≈.28°) of each TDRS KSA antenna, establishing and maintaining a communications link requires autotrack for both the user SC and TDRS. The TDRS autotrack is unique in that most of the autotrack hardware is on the ground rather than in the satellite.

Acquisition of KSA autotrack is accomplished by either of two sequences. In the first sequence, TDRS illuminates the user SC with a reduced level (+40dBW); the user SC searches, acquires, illuminates the TDRS; and TDRS acquires the signal from the user, thereby completing acquisition. During this low power acquisition, no data modulates the carrier; only the PN sequence is sent. In

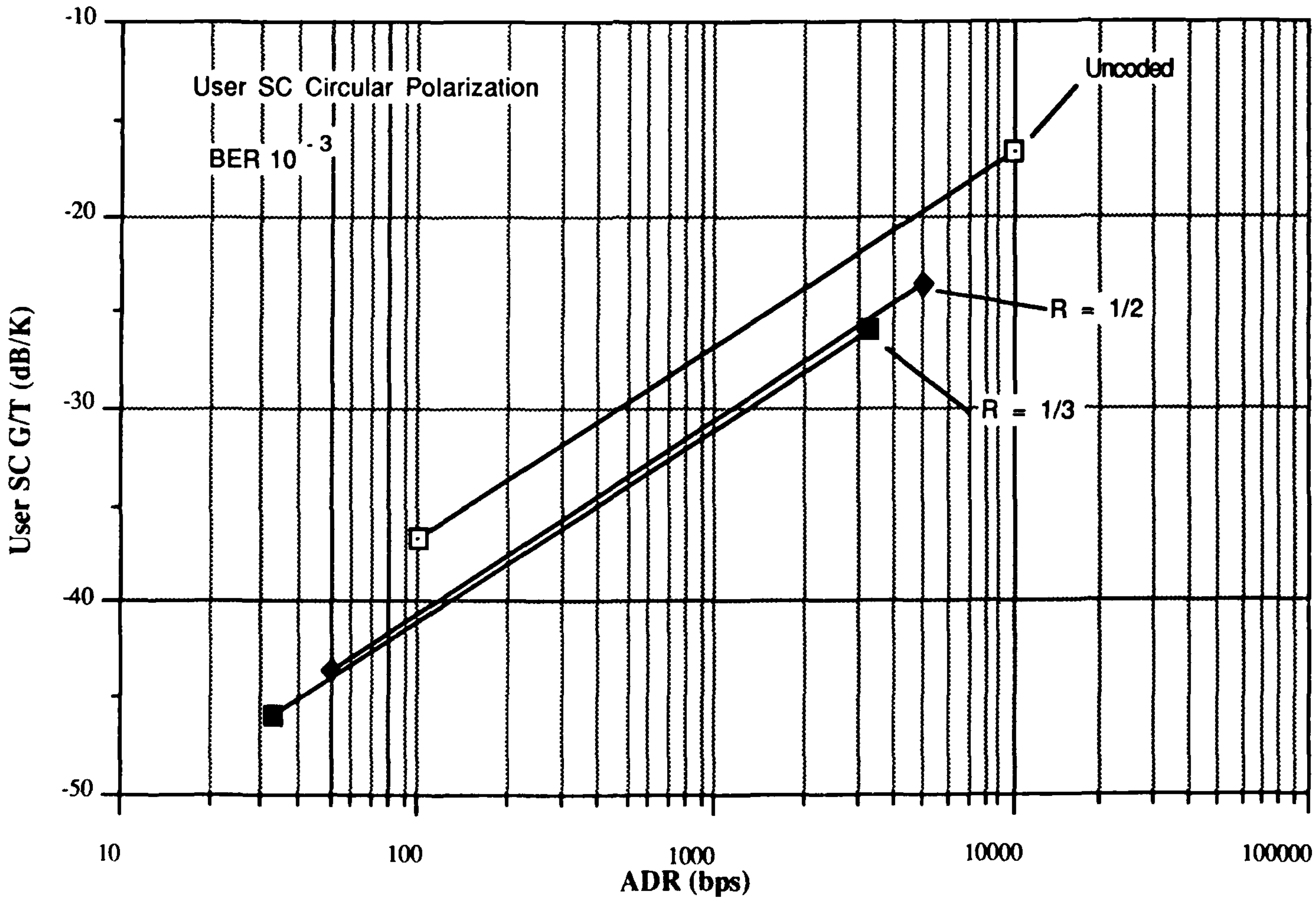


Figure 5-3
MA Forward Services Circular Polarization

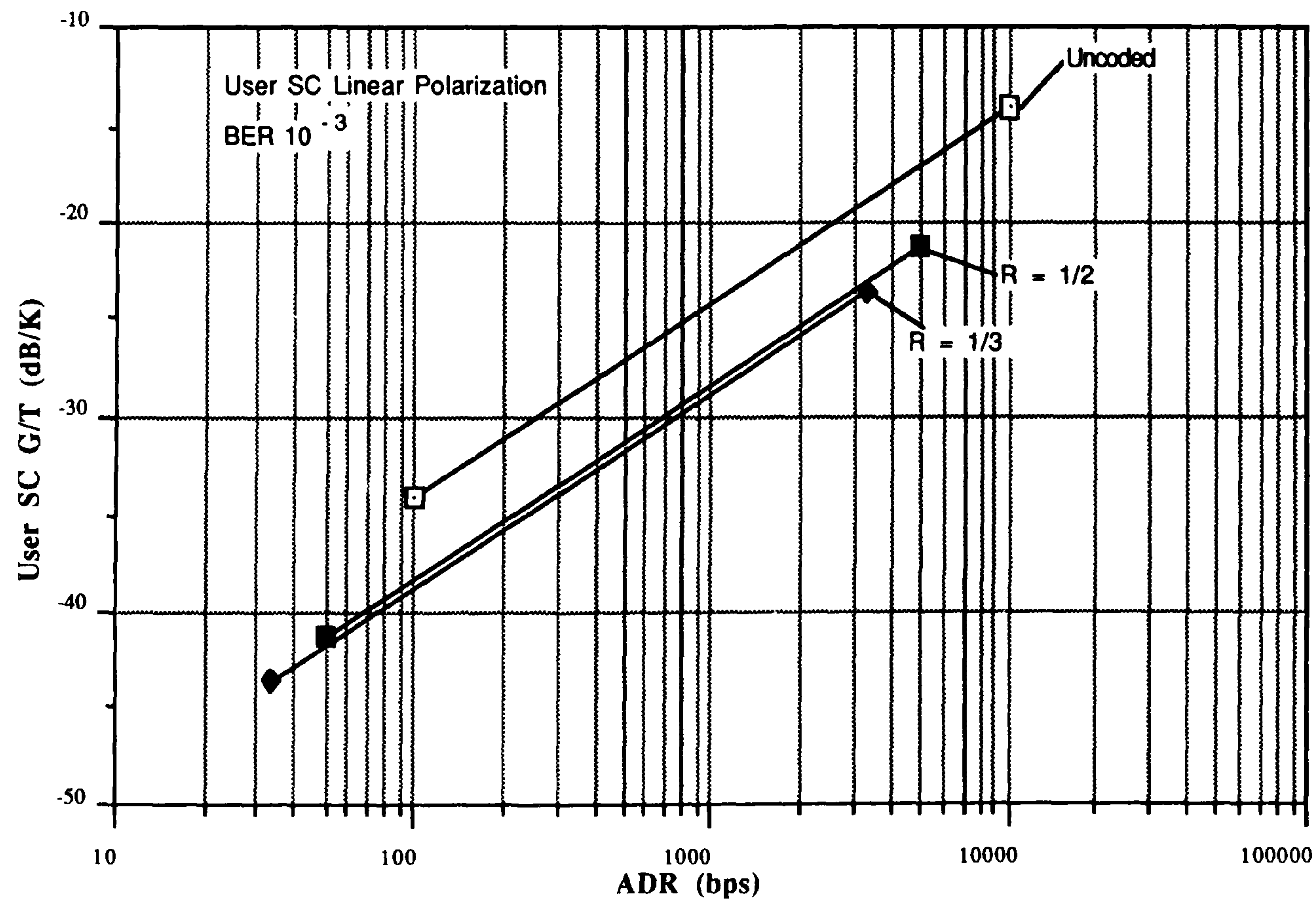


Figure 5-4
MA Forward Services Linear Polarization

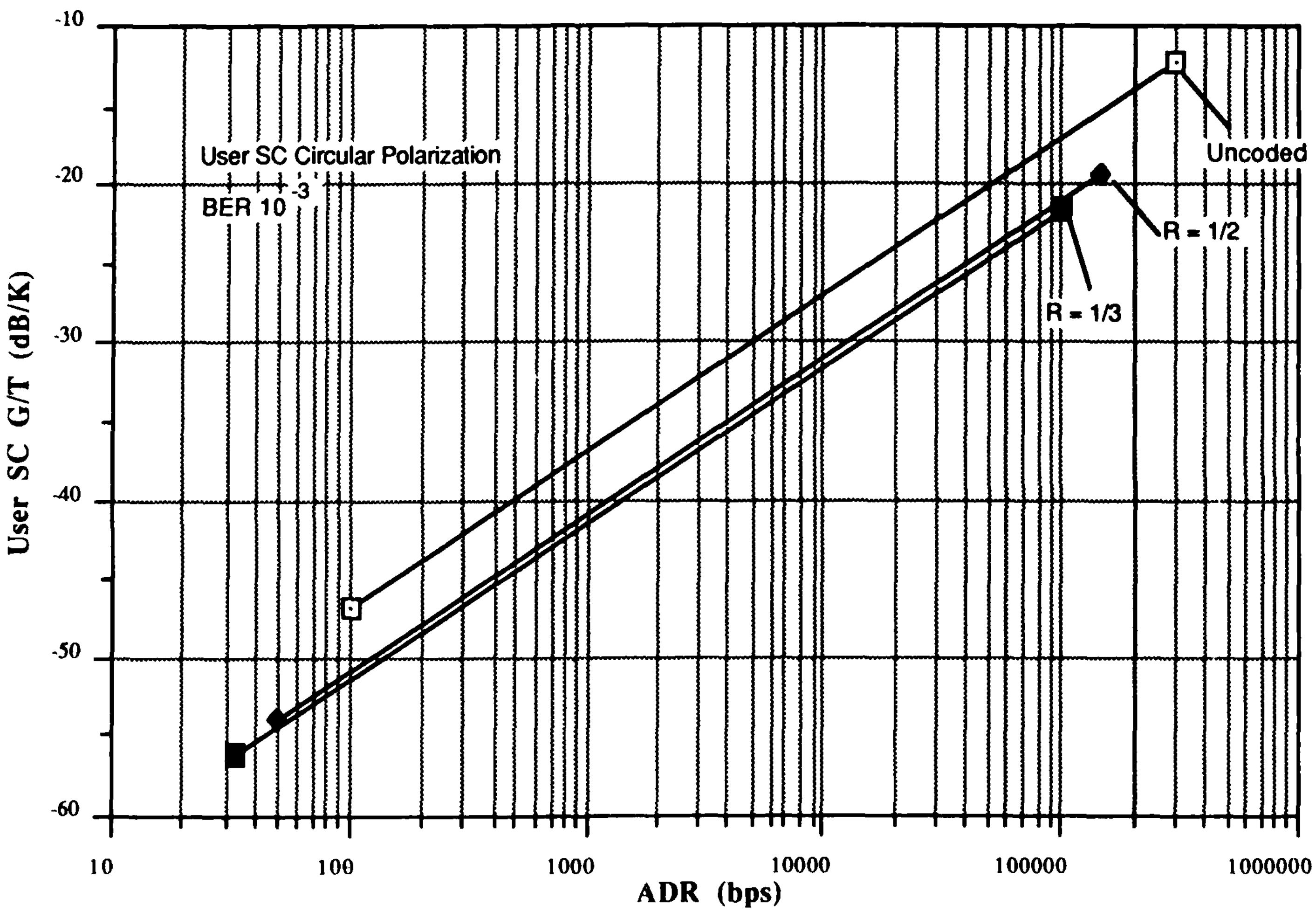


Figure 5-5
SSA Forward Services Circular Polarization

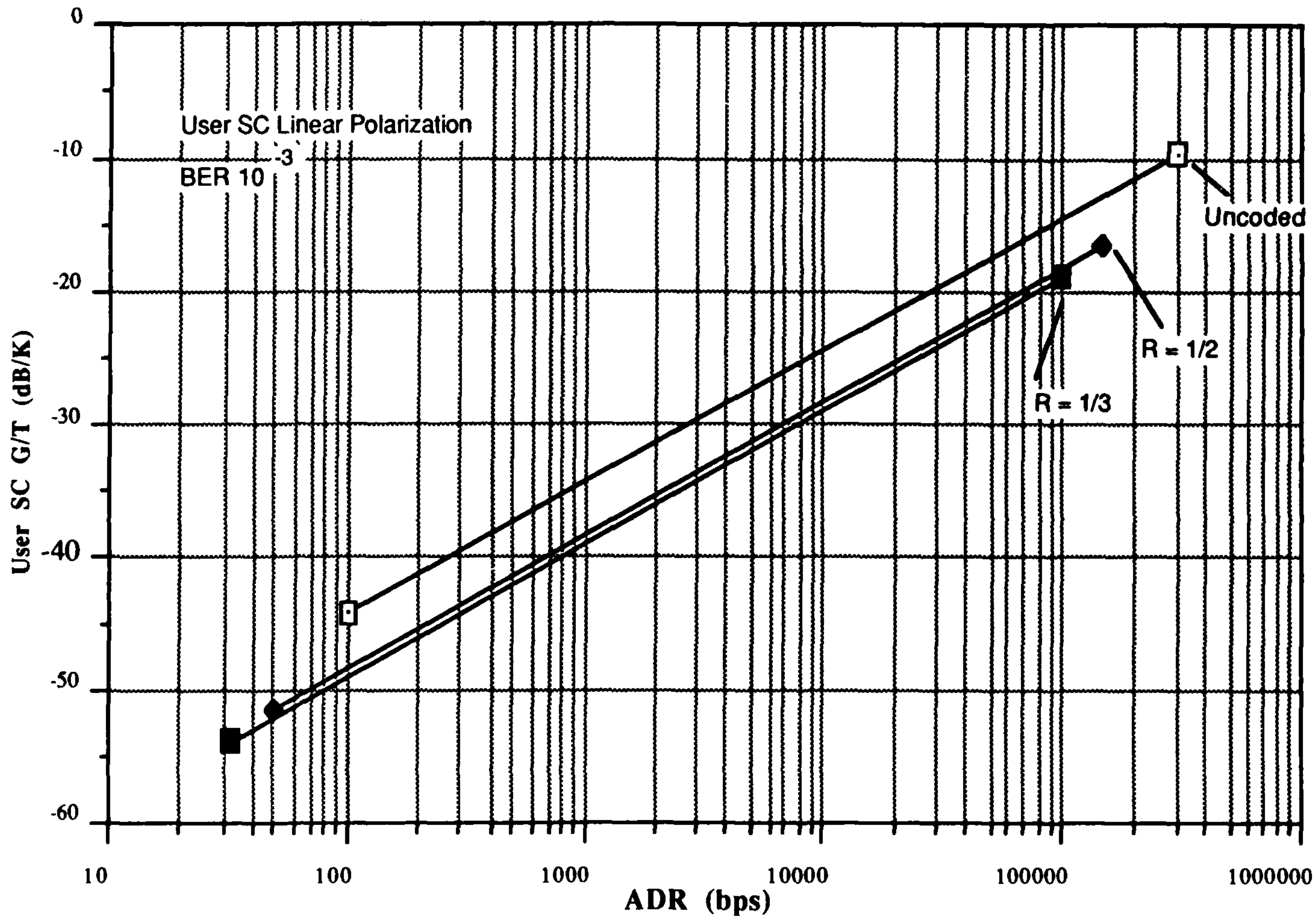


Figure 5-6
SSA Forward Services Linear Polarization

the second sequence, the user SC illuminates the TDRS with a minimum of -179.2 dBW (at the TDRS); TDRS searches and acquires and illuminates the user; the user acquires and acquisition is complete.

From these scenarios it is clear that forward and return service are closely intertwined. The level of equipment complexity is made much higher by autotrack requirements. Once acquisition is complete, the TDRS will switch to normal power mode of 46.5 dBW. Like SSA, a high power mode is available for emergency conditions. From Table 3-6, KSA forward services allow a wide range of data rates (1 kbs - 25 Mbs). If data rates are greater than 300 kbs, PN code modulation is not used and the user SC can expect to pick up about 1 dB in performance. Link equations are

$$G/T = 10\log ADR + E_b/N_0\,req - G_c - PN - 60.1 \tag{5.15}$$

for circular polarization, and

$$G/T = 10\log ADR + E_b/N_0\,req - G_c - PN - 57.6 \tag{5.16}$$

$$PN = 0 \text{ for } ADR \leq 300 \text{ kbs}$$

$$= 1 \text{ for } ADR > 300 \text{ kbs}$$

for linear polarization. Reference charts in Figures 5-7 and 5-8 apply.

D. RETURN LINK

A re-examination of Tables 3-3, 3-5, and 3-7, show many possible signal structures for the return link. In particular, unbalanced power ratios are allowed on the I and Q channels in some modes of operation. Often this ratio will be directly proportional to data rates on the two channels. NASA gives the following rules for calculating power received (P_{rec}) at the TDRS; [Ref. 2:p. 3-59]

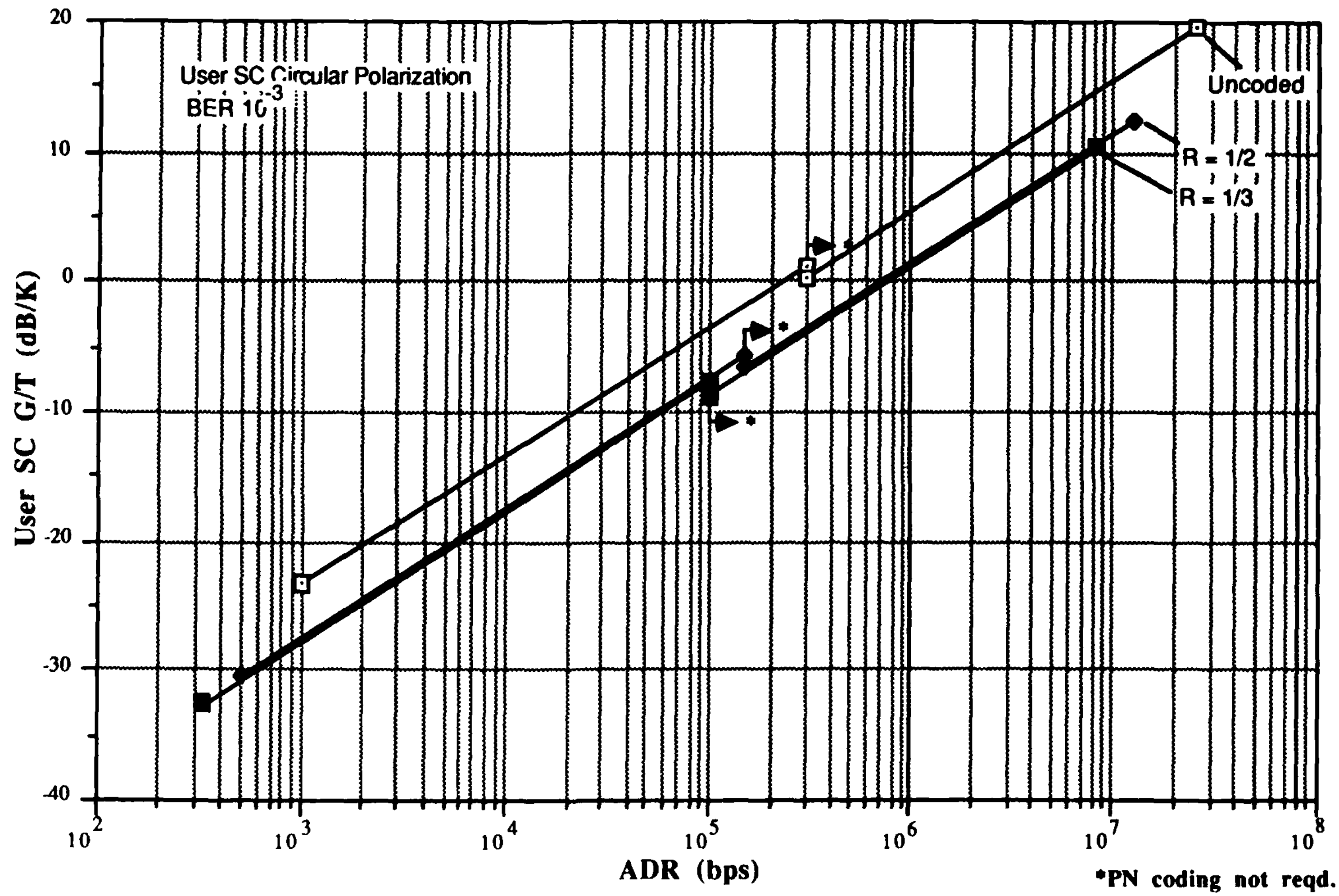


Figure 5-7
KSA Forward Services Circular Polarization

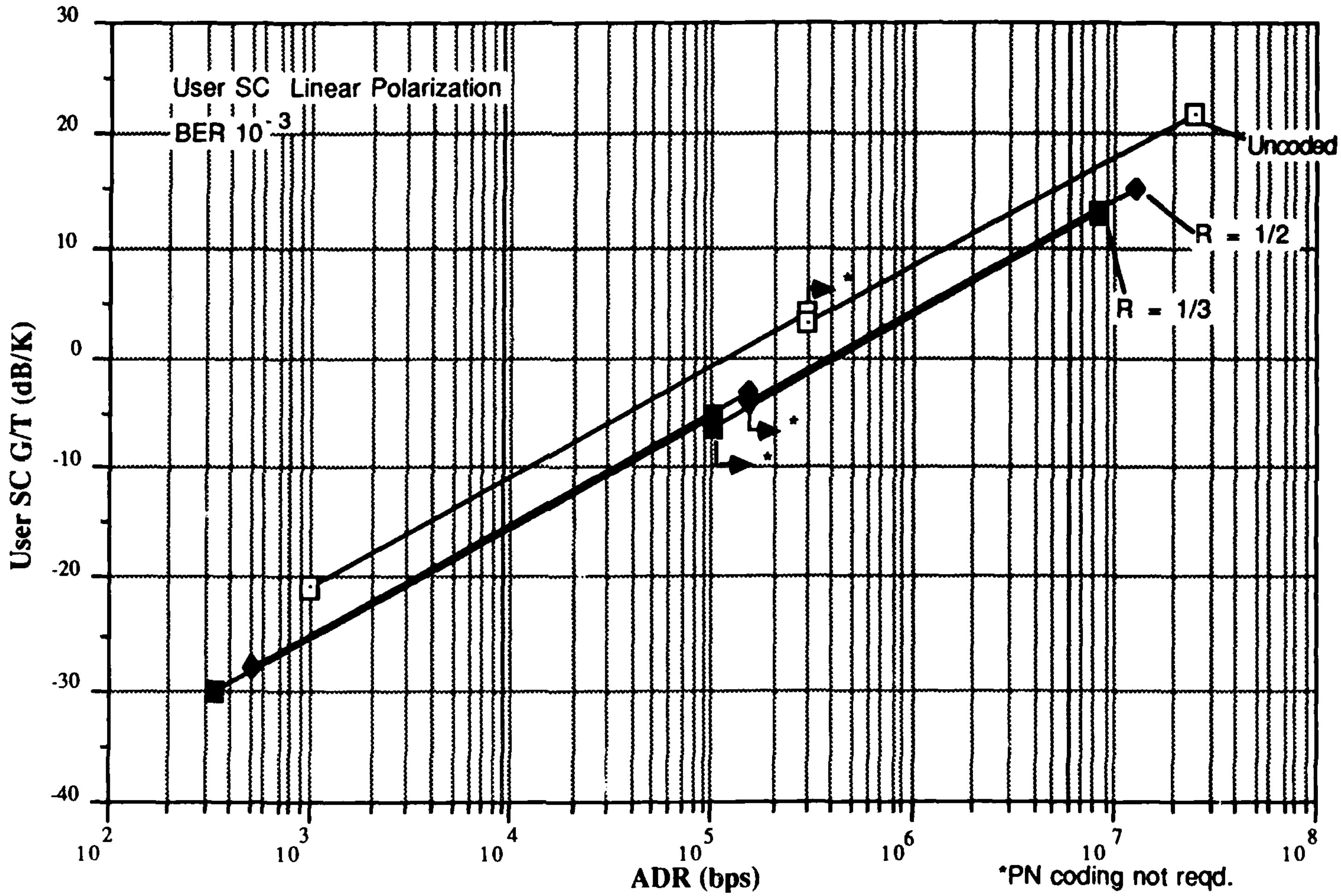


Figure 5-8
KSA Forward Services Linear Polarization

- For QPSK signals (balanced or unbalanced) with non-identical data on the I and Q channels, the P_{rec} value is to be interpreted as the minimum P_{rec} per channel.
- For balanced QPSK signals with identical data on the I and Q channels, the minimum required P_{rec} is to be interpreted as the total (I+Q) P_{rec}.
- For unbalanced QPSK signals with identical data on the I and Q channels, the minimum P_{rec} is to be interpreted as the P_{rec} of the stronger channel.

The return link power budget by NASA addresses only the parameters between the user SC and the input to the TDRS antenna. User EIRP is defined as [Ref. 8:p. A-12]

$$EIRP = G + P_{tx} + L \quad (dBW) \tag{5.17}$$

where G = user SC antenna gain (dB)

P_{tx} = user transmitter power (dBW)

L = user passive losses (dB)

and power received at the TDRS is

$$P_{rec} = EIRP + L_s + L_p + L_\Theta + L_{RFI} \quad (dBW) \tag{5.18}$$

where L_s, L_p, L_Θ are same as for forward link

L_{RFI} = Radio frequency interference loss (≤ 0 dB)

NASA provides power required for a 10^{-5} BER link as [Ref. 8:p. A-13]

$$P_{req} = 10\log ADR - X - FSL \tag{5.19}$$

where X and FSL are constants provided in Table 5-2. [Ref. 8:p. A-14]

The X values include losses through the TDRS, any coding gains, and losses at the ground station interface. The operating margin is

$$M = P_{rec} - P_{req} \tag{5.20}$$

TABLE 5-2 A. VALUES FOR X (dB)

Service	MA	SSA		KSA
No coding				
DG 1				
mode 1				27.0
mode 2	N/A	N/A		27.0
mode 3				
I Channel				27.0
Q Channel				28.0
DG2				28.0
Coded				
DG 1	R=1/2	R=1/2	R=1/3	R=1/2
mode 1	24.6	34.1		32.2
mode 2	24.6	34.1		32.2
mode 3	N/A			
I Channel		34.1		32.2
Q Channel		35.1	33.3	33.2
DG 2	N/A	35.1		33.2

TABLE 5-2 B. VALUES FOR FSL (dB)

Service	FSL
MA	192.8
SSA	192.8
KSA	209.8

Rearranging these equations yields

$$EIRP = 10\log ADR - X - FSL + M - L_s - L_p - L_\Theta - L_{RFI} + \Delta E_b/N_o\,req + \Delta G_c$$

where $\Delta E_b/N_o$ req is the difference between E_b/N_o req. at a BER of 10^{-5} (5.21)

and that of the desired BER

> 0 for BER $< 10^{-5}$

< 0 for BER $> 10^{-5}$

ΔG_c is difference between coding gains achieved at BER of 10^{-5} and that of the desired BER

$$< 0 \text{ for BER} < 10^{-5}$$
$$> 0 \text{ for BER} > 10^{-5}$$

Whatever coding schemes or data formats are used, care must be taken to remain within the bandwidths provided. In addition each return service has a floor for its P_{rec} for acquisition and tracking purposes. This determines the lowest EIRP allowable at any service. Figure 5-9 shows MA service as do Figures 5-10 and 5-11 for SSA, and Figures 5-12 and 5-13 for KSA respectively. All charts are referenced to a BER of 10^{-5}. Adjustments can be made by accounting for the last two variables of equation 5.21.

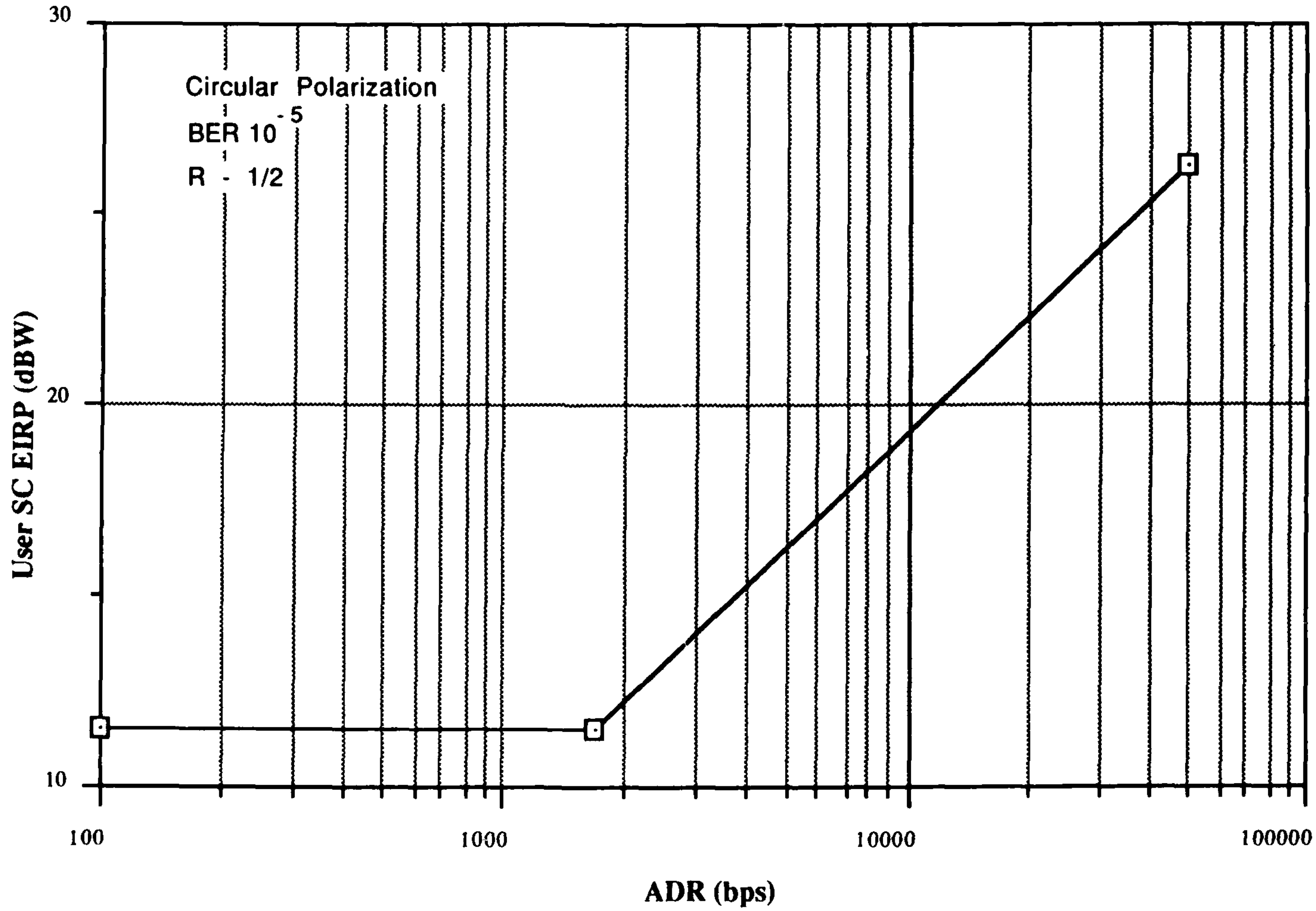


Figure 5-9
MA Return Services

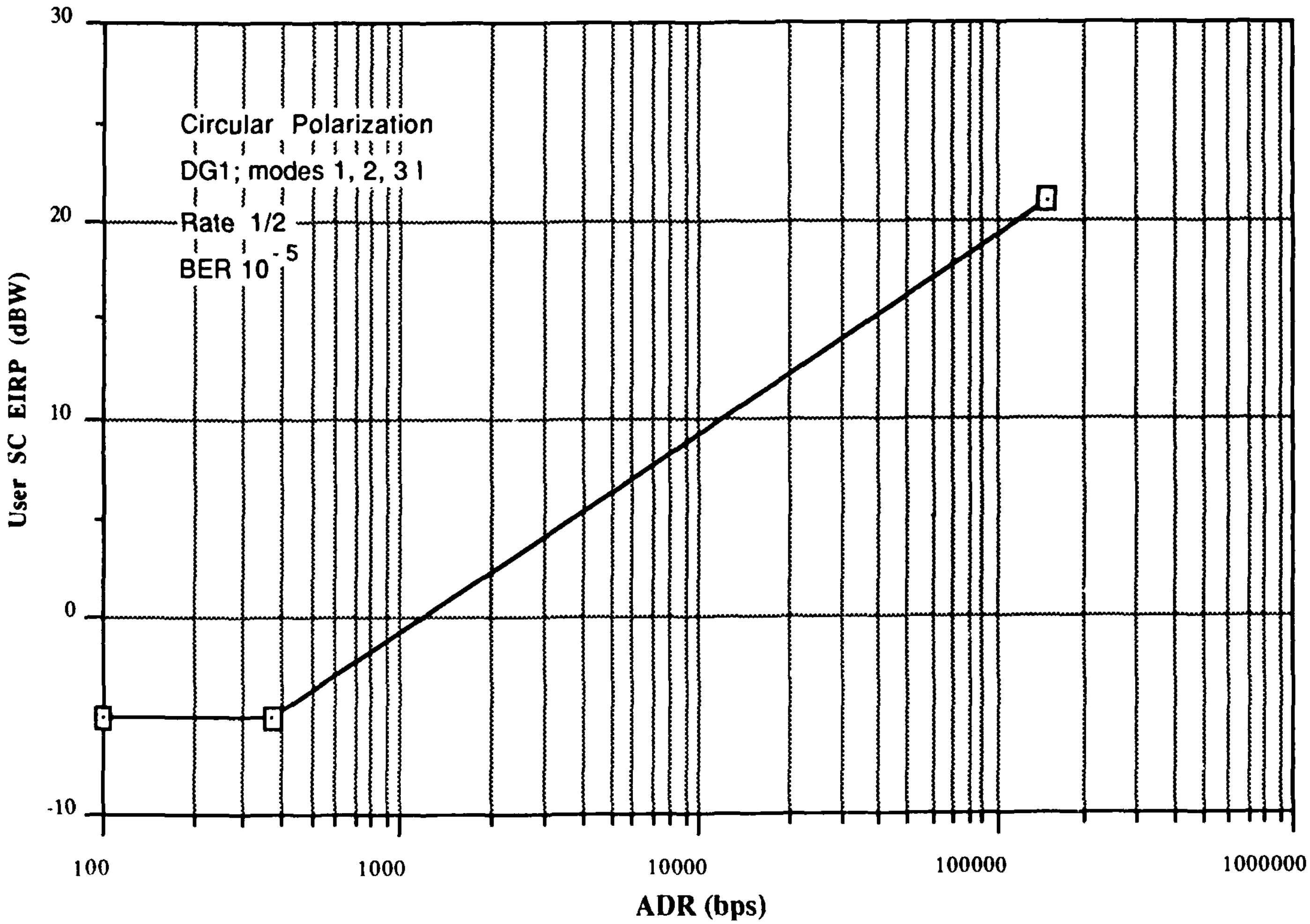


Figure 5-10
SSA Return Services DG1 Modes 1, 2, 3 I

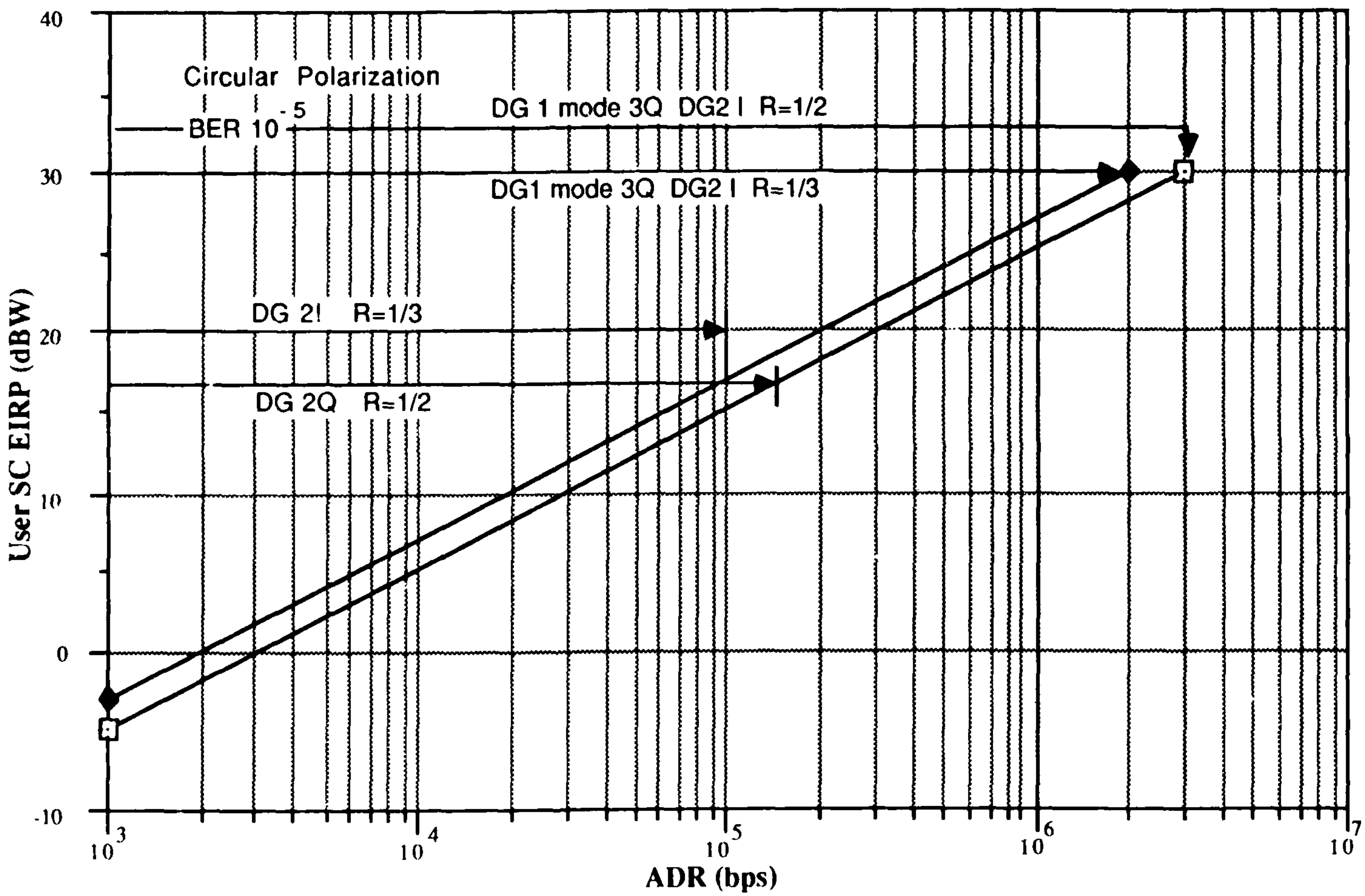


Figure 5-11
SSA Return Services DG1 Mode 3Q and DG2

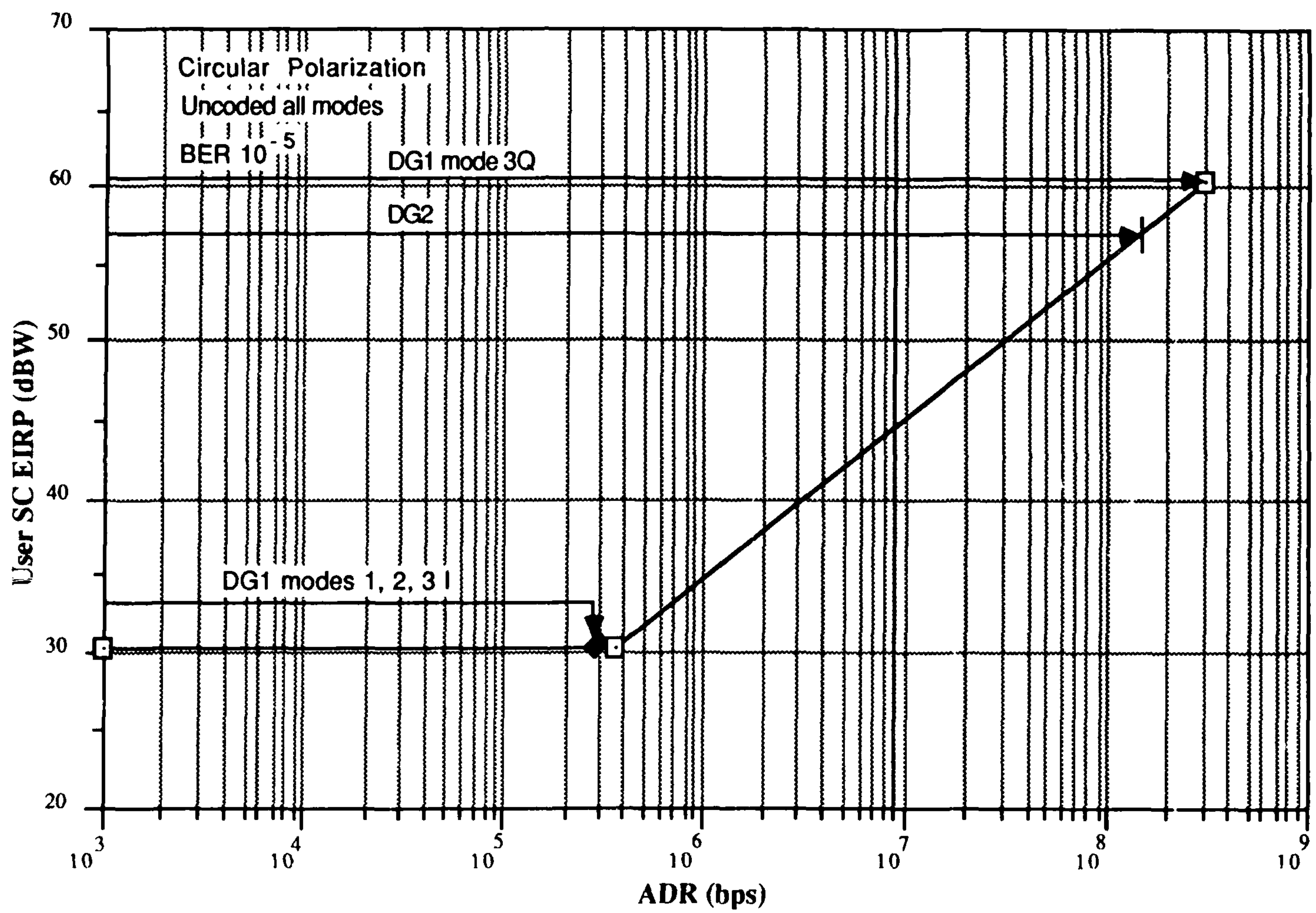


Figure 5-12
KSA Return Services Uncoded, All Modes

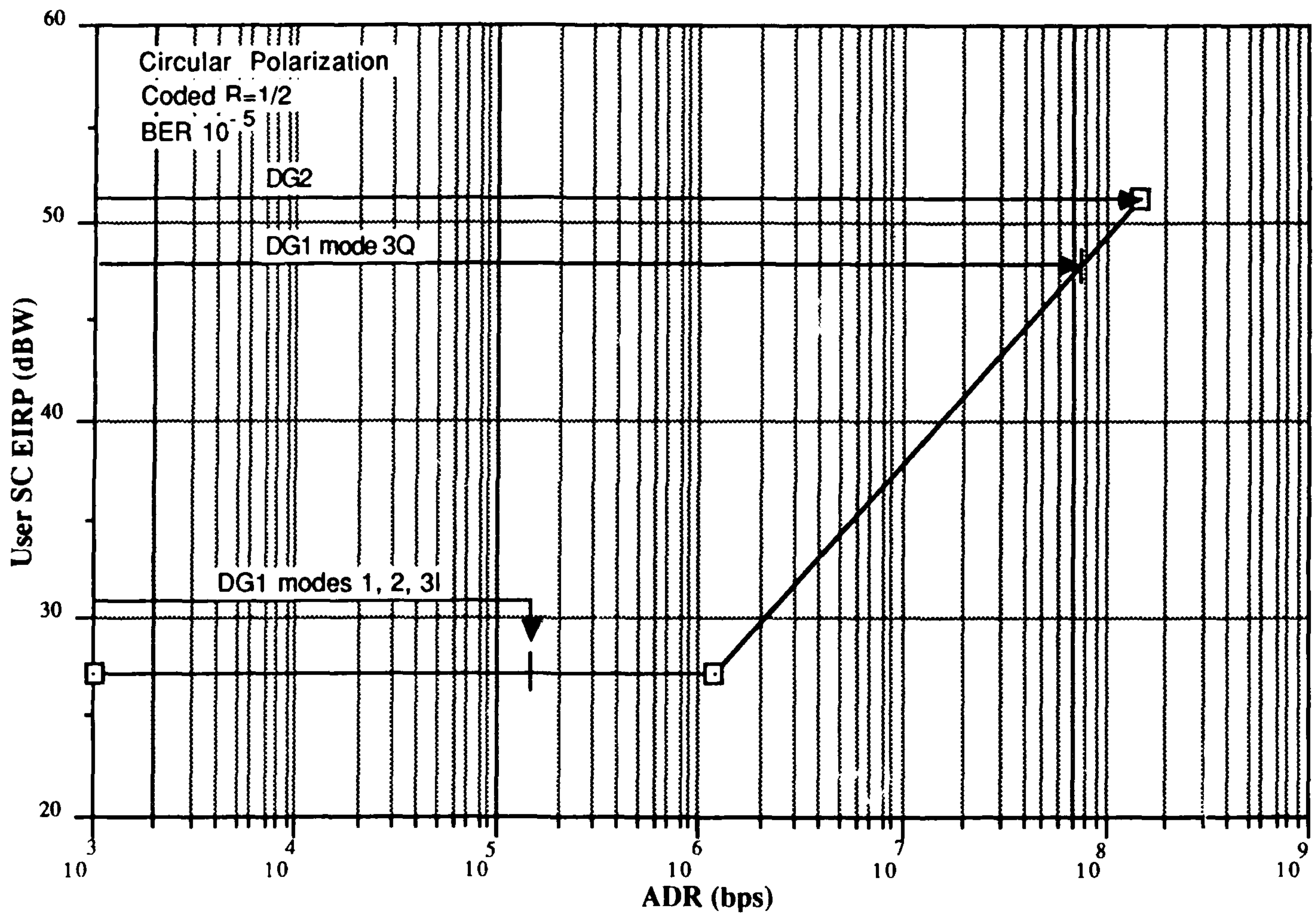


Figure 5-13
KSA Return Services Code R = 1/2, All Modes

VI. COST AND DOCUMENTATION REQUIREMENTS

A. INTRODUCTION

The technical complexity of the TDRSS Network requires early and frequent involvement of NASA in the user planning and design stages. NASA requires a minimum of three years before planned launch for notification of intent to exploit TDRSS assets. During the intervening period numerous technical and operational details will require resolution and documentation. In addition, expected charge schedules will be negotiated and contractually agreed upon. This chapter will give a top level view of required documentation and elements defining the costing structure.

B. COST STRUCTURE

When the user project decides to begin work with NASA on developing services, an initial non-refundable administrative charge of $25,000 is required. This sum will be applicable to future TDRSS operational service charges. During the pre-launch phase, standard services such as mission planning, documentation, link analysis, testing, computer, human resources, etc., will be assessed to the user project on a cost basis and are due the government prior to NASA rendering such services.

Actual TDRSS operational service charges are set by NASA Headquarters each October for the following calendar year. Any rate variations year to year reflect changes in operating costs, loading formulas and escalation. Table 6-1 shows 1988 service charges and adjustment factors. The most current status of operational rates can be found in References 11 and 12.

TABLE 6-1 TDRSS OPERATIONAL SERVICE RATE STRUCTURE

Service		Non-NASA Government User	Non - U.S. Government User
Single Access		$74/minute	$128/minute
Multiple Access Forward Service		$16/minute	$24/minute
Multiple Access Return Service		$5/minute	$9/minute
Adjustment Factors	**Flexible**	**Time or Position Constrained**	**Emergency or Disruptive**
Single Access Service	.5	1	2
Multiple Access Forward Service	.67	1	2
Multiple Access Return Service	N/A	1	2

The actual per minute charge for TDRSS service is computed by multiplying the charge per minute for the appropriate service by the number minutes scheduled and the appropriate adjustment factor.

C. DOCUMENTATION

Figure 6-1 [Ref. 2:p. 1-7] depicts the collaborative effort and documentation flow from initial planning stages up to the operational phase. This process can be broken into two phases: the system definition phase and the system implementation phase.

Note

1. Bilateral Project/TDRSS CCB-controlled documents
2. Unilateral Project CCB-controlled documents.
3. Bilateral Project/800 Directorate Council-controlled document.
4. Code 800-controlled documents.
5. Multiorganization-controlled documents.
6. Code 800 Directorate Council-controlled documents.

SIRD:
Configuration-controlled by Project and Headquarters Code T.

NSP:
Configuration-controlled by Code 500, Code 800, and Headquarters Code T.

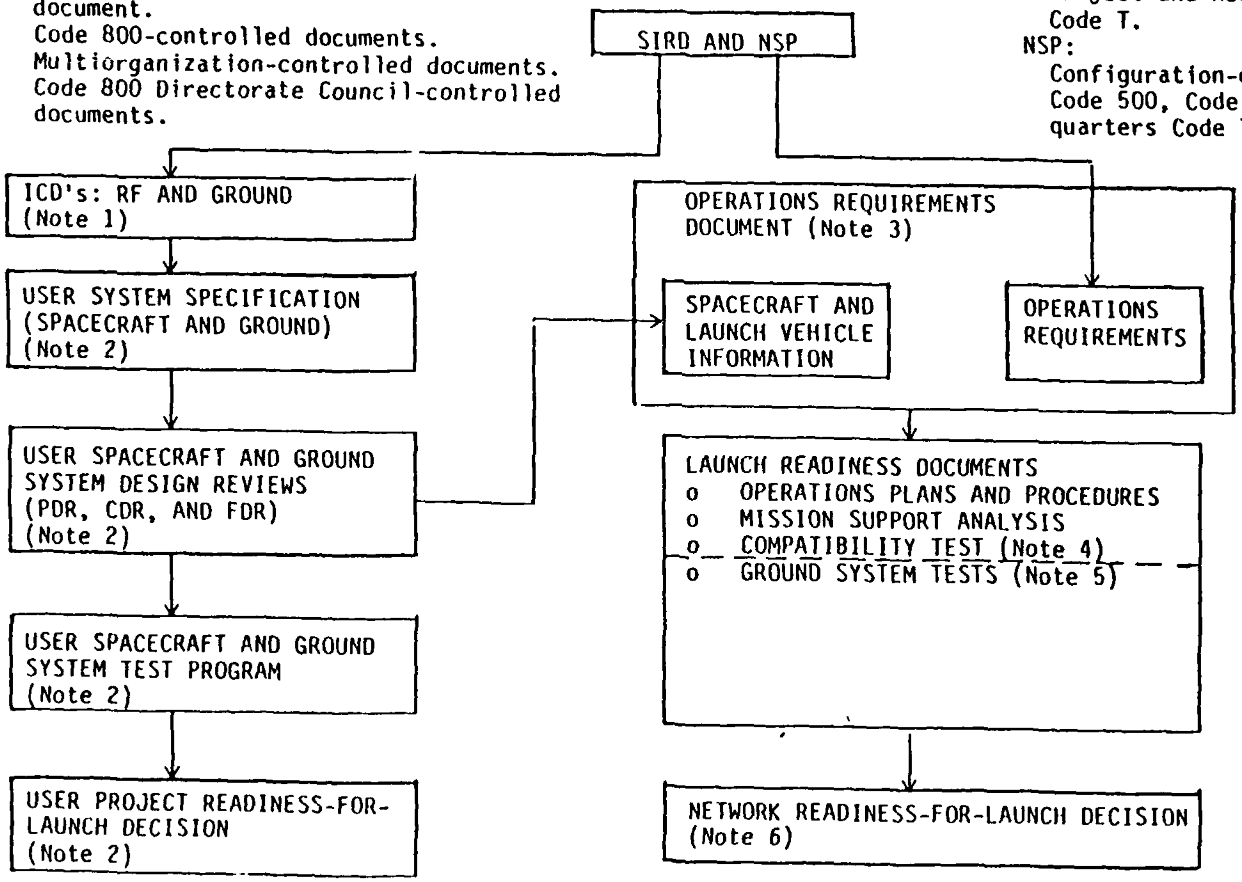


Figure 6-1
Documentation Hierarchy

1. System Definition Phase

This phase is a process to match user needs with TDRSS capabilities and limitations. The user SC project office initiates the process by submitting a Support Instrumentation Requirements Document (SIRD) to NASA's Office of Space Tracking and Data Systems (OSTDS). It contains a project description, project objectives, and the general baseline requirements of the project. Submission is not later than 36 months prior to planned launch of the user SC.

NASA, in turn, responds to the request for services with the NASA Support Plan (NSP). It formally accepts the request and authorizes commitment of tracking and data acquisition resources. The NSP is a point-by-point response to the user SIRD. Reference 13 contains the exact format and procedures for preparing the SIRD.

Derived from the SIRD, the user/Network Directorate commitments are detailed in the RF Interface Control Document (ICD) and the Ground ICD. The ICD's contain specific interface detail agreements. Their purpose is to ensure technical compatibility between the user systems and the TN. The RF ICD details data formats, service type, signal design and link parameters. Ground ICD's cover the ground data and operations message format between the user ground segment and NCC/NASCOM. References 14 and 15 contain instructions for preparation of the RF and Ground ICD's respectively.

After the ICD's are prepared, the user space and ground system specifications are established by the user project. The Network Support Committee (NSC) will provide technical assistance to the user in an advisory capacity in the preparation of specifications and other documentation.

Simultaneously with the ICD preparation, the Operations Requirements (OR) document is begun by the user project. It contains the specific detailed operational requirements for the project or mission. A major portion of the OR relates to the definition of configuration codes and their development. These codes are used in service requests to automatically configure the TDRSS for the type of service requested. Once the codes are agreed upon, they are entered into the NCC data base. Although prepared by the user project, NASA support element representatives will sign off portions pertinent to their areas of responsibility. The OR must be submitted no later than 24 months prior to planned launch. Reference 16 gives detailed instruction for OR preparation.

2. System Implementation Phase

This phase is the iterative process of fielding a final spacecraft model. The user project personnel and NASA Network Directorate personnel will work closely in the design, analyses, tests and simulations needed for project completion. The objective of the process is to identify incompatibilities requiring correction by negotiation between the user and the Network Directorate.

The OR is completed during this phase with addition of refined operations requirements and spacecraft and launch vehicle information. NASA prepares from this the operations plans and procedures, performs mission analyses, and performs the compatibility tests and simulations.

Although the user does not prepare the following documents, user interface is required during their preparation by the appropriate NASA support personnel:

- Network Loading Analysis
- RF Link Margin and Coverage Analysis
- Compatibility Test Report

- User/TDRSS Operational Simulation Report
- Orbit Support Analysis
- Operations Readiness Reviews (ORR)

Upon satisfactory completion of activities in the implementation phase, both the user project and the Network readiness-for-launch decisions are made. Upon favorable decisions, the project is ready for launch and full scale operations.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The TDRSS Network holds great potential for servicing a variety of LEO "lightsat" missions. Particularly appealing is the wide range of data rates supported and accurate positioning capabilities. Even with orbit coverage limitations, TDRSS is clearly superior to other present alternatives. With the wide range of communication services provided, TDRSS may be suitable for only a part of the mission needs of the design satellite such as command data.

The parameters delineated in this report give the tools for an early determination of the applicability of the Network to a particular mission. From the link analysis of preceding chapters, it can be generally inferred that the forward link will offer little difficulty to maintain up to moderate data rates for relatively simple receivers. On the other hand, the minimum Prec for the TDRS acquisition and tracking requires the user SC to have a moderate or high gain antenna system, moderate power transmitter, or both. Conversely, if the Prec can be met, the ADR ranges are fairly large for return traffic. MA and SSA return service would be the likely candidates for use with the simple "lightsat" concept. KSA return services would require an extremely sophisticated tracking mechanism to maintain the interface with the TDRS. Such a level of complexity negates the very concept of a simple low-cost satellite.

Concurrent with TDRSS development, NASA commissioned several studies to develop antenna systems that could fill the needs of low power LEO satellites. One of the studies identifies various electro-mechanically steered antenna systems for

possible use aboard user SC.[Ref. 13] The other study is the design of electronic switching spherical array antenna systems.[Ref. 16] Each of these types of systems has inherent advantages and disadvantages. In general, the electro-mechanical antennas provide higher gains than the electronic switched arrays but introduce stabilization problems to the spacecraft. Likewise, the electronic switched arrays introduce noise to the signal from the switching process. Both types come in a variety of sizes and available gains. Without an antenna of these types, the return link utility is little unless unrealistically high transmitter powers are used.

A gauge of what power level requirements will be placed on spacecraft power buses can be gleaned from the power ratings of the standard NASA transponder.[Ref. 14] The transponder has three possible transmit levels: 1 watt, 2.5 watts, and 5 watts. The required input powers to achieve each are 21.5, 31.0, and 40 watts respectively. The higher than normal power requirements can be traced to buffering and decoding circuitry required by the TDRSS design. A user designed transponder could expect lower requirements because the NASA design in universal to all services.

B. DECISION HIERARCHY

For a useful analysis of the TDRSS option, the mission itself must be defined as to acceptable performance, development schedule, and allowable cost. Once these basic features are identified, the TDRSS decision hierarchy can proceed as follows;

- Link Analysis - the power budget requirements on the spacecraft will determine much of its size, stabilization, antenna structure and costs. The mission performance levels establish acceptable data rates for mission execution that in turn determine which TDRSS service or services will be necessary. From the planning charts of chapter five, close approximations for levels of quality will yield a range of EIRP's to the planner. If acceptable in terms of the spacecraft design, the process can proceed.

- Orbit Considerations - from chapter four, the primary factors in orbit consideration are variable ranging, mutual acceleration, and TDRSS coverage. Ranging will have a relatively minor effect on the link analysis, but can add a margin level to performance. Likewise, acceleration was shown to be within limits for a non-maneuvering satellite. When and how to perform maneuvers must be determined to ensure adequate acquisition times. More critical to any mission is the TDRSS coverage. If the geographic gap is unacceptable, then a gap filler alternative must developed or a short time recorder must be used. Whatever the case, this will raise both the overall costs and the spacecraft weight budget and power allocations.
- Cost and Documentation - costs as listed in chapter six will very likely be small as to overall operational costs over the spacecraft life. Documentation requirements and accompanying timelines must be overlaid standard Defense Department acquisition requirements. There will be yet another agency to move the project through. Realistic assessments must be made as to whether or not all requirements and timelines can be met simultaneously. Otherwise, special work around arrangements must be established.
- TDRSS Network - the complete operational network must be examined in terms of security, flexibility towards military needs and level of survivability in the event of conflict.

After several iterations of the preceding criteria, an informed decision can be made to use the TDRSS Network. Many technical hurdles remain, but NASA can and will provide full support in resolving them.

APPENDIX A: RANGING COMPUTER PROGRAM

The following TurboBasic program allows the user to get a timed stepped distance calculation between each TDRS and the prospective spacecraft. It is an interactive program requiring the user input orbit altitude and inclination. The program starts from a sub satellite point of 0° lat., and 0° long. The user will also input a desired number of orbits for examination. This program takes into account orbit precession and is accurate enough for initial planning.

```
'
'
'
'
'
'              *************************
'              *  TDRS RANGING         *
'              *  PROGRAM FOR USER     *
'              *  SATELLITE PLANNERS   *
'              *************************
'
'
'
'
'-------------------------------------------------INITIALIZE
```

```
'
CLS
OPEN "B:RANGE.OUT" FOR OUTPUT AS 1
'
'
'------------------------------------------------------INPUT
'
PRINT "THIS PROGRAM CALCULATES LINE OF SIGHT RANGING OF TDRS-
EAST"
PRINT "AND TDRS-WEST AS A FUNCTION OF USER INPUT ORBIT ALTITUDE
AND INCLI-"
PRINT "NATION, AND NUMBER OF ORBITS.  IT ALSO PROVIDES
INCREMENTAL SUB-"
PRINT "SATELLITE LATITUDE AND LONGITUDE FOR EACH DAY OF ORBIT.
STARTING"
PRINT "LATITUDE AND LONGITUDE ARE 0,0 AT TIME 0.  OUTPUT FILE IS
RANGE.OUT." PRINT
PRINT
PRINT
PRINT
PRINT
INPUT "INPUT ORBIT ALTITUDE (KM)=";HO
PRINT
INPUT "INPUT ORBIT INCLINATION (DEG)=";I
PRINT
```

```
INPUT "INPUT DESIRED NUMBER OF ORBITS=";NO
'
'-----------------------------------------------SET CONSTANT VALUES
'
'
DEFSTR A
DEFDBL J,T,U,C,P,R,D,G,B
A=" TDRS RANGING AS A FUNCTION OF SATELLITE ORBIT"
A1=" ********************************************"
A2="OBSCURED"
A3="ORBIT NO  DAY-HR-MIN   LAT    LONG   TDRS-E    TDRS-W"
A4="                                RANGE KM   RANGE KM"
A5=" ##       ## ## ##    ####.#   ####.#   #####.#   #####.# "
A6=" ##       ## ## ##    ####.#   ####.#   #####.#   \    \"
A7=" ##       ## ## ##    ####.#   ####.#  \    \ #####.# "
A8=" ##       ## ## ##    ####.#   ####.#  \    \ \    \"
IF I=90 THEN I=89.9
J=.00108265
TD1=-41.0
TD2=-171.0
U=398601.2
CH1=319
CH2=189
PI=4*ATN(1)
RAD=PI/180
```

```
RE=6.378165E03
RO=RE+HO
RIN=RE/RO
CH3=(81.317/180) * PI + PI/2 - ATN(RIN/SQR(1-RIN^2))
T1=PI/30 * SQR(RO^3/U)
W1=2*PI/T1
W2=(1.5*J*SQR(U/RO^3)*RE/RO^2)/1440
W3=(.25-W2)*RAD
N=39
GEO=42164
XE=GEO*COS(TD1*RAD)
YE=GEO*SIN(TD1*RAD)
XW=GEO*COS(TD2*RAD) YW=GEO*SIN(TD2*RAD)
PHA=8.7*RAD
BETA=ATN(RIN/SQR(1-RIN^2))
TAU=PI-PHA-BETA
RMAX= SIN(TAU) * GEO/RIN
'
'-------------------------------------------------PRINT PARAMETERS
'
PRINT#1,A
PRINT#1,A1
PRINT#1,
PRINT#1,
PRINT#1,
```

```
PRINT#1,"ORBITAL PARAMETERS USED"
PRINT#1,
PRINT#1, USING "ORBIT ALTITUDE=####### KM";HO
PRINT#1, USING "ORBIT INCLINATION=###### DEGREES";I
PRINT#1, USING "NUMBER OF ORBITS=#######";NO
PRINT#1, USING "TDRS EAST LONGITUDE=#######.## DEGREES ";TD1
PRINT#1, USING "TDRS WEST LONGITUDE=#######.## DEGREES";TD2
PRINT#1, USING "ORBIT PERIOD=#####.## MINUTES";T1
PRINT#1,
PRINT#1,
PRINT#1, A3
PRINT#1, A4
PRINT#1,
X1=COS(CH1*RAD)  : X2=COS(CH2*RAD)
Y1=SIN(CH1*RAD)  : Y2=SIN(CH2*RAD)
Z1=0 : Z2=0
'---------------------------------------------CALCULATE LAT/LON
'
FOR T=0 TO NO*T1 STEP T1/40
   X3=COS(W1*T)*COS(W3*T) + SIN(W1*T)*SIN(W3*T)*COS(I*RAD)
   Y3=-COS(W1*T)*SIN(W3*T) + SIN(W1*T)*COS(W3*T)*COS(I*RAD)
   Z3=SIN(W1*T)*SIN(I*RAD)
   N=N+1 : K=INT(N/40)
   D=INT(T/1440) : H=INT((T-1440*D)/60) : M=T-1440*D-60*H
   D1=X2*X3 + Y2*Y3 + Z2*Z3
```

```
D2=X1*X3 + Y1*Y3 + Z1*Z3
LA=(ATN(Z3/SQR(1-Z3^2)))/RAD
LN=(ATN(Y3/X3))/RAD
IF X3>0 AND Y3<0 THEN LN= 360 + LN
IF X3<0 AND Y3>0 THEN LN= 180 + LN
IF X3<0 AND Y3<0 THEN LN= 180 + LN
LT=INT(LA*10+.5)/10 : LM=INT(LN*10+.5)/10
'--------------------------------------------CALCULATE RANGE
XP=RO*COS(LM*RAD)*COS(LT*RAD)
YP=RO*SIN(LM*RAD)*COS(LT*RAD)
ZP=RO*SIN(LT*RAD)
RE=SQR((XE-XP)^2 + (YE-YP)^2 + ZP^2)
RW=SQR((XW-XP)^2 + (YW-YP)^2 + ZP^2)
IF RE > RMAX AND RW > RMAX THEN PRINT#1, USING A8;K,D,H,M,LT,LM,A2,A2
ELSE
IF RE <= RMAX AND RW <= RMAX THEN
PRINT#1, USING A5;K,D,H,M,LT,LM,RE,RW
ELSE
IF RW > RMAX AND RE <= RMAX THEN
PRINT#1, USING A6;K,D,H,M,LT,LM,RE,A2
ELSE
PRINT#1, USING A7;K,D,H,M,LT,LM,A2,RW
END IF : END IF
END IF
```

```
  NEXT T
CLOSE
END
```

APPENDIX B: TDRS AVAILABILITY PROGRAM

This program is adapted from the methodology used in Reference 5 to assess the suitability of TDRSS to fill the mission needs of LANDSAT. Although not perfectly accurate, it will yield results that are sufficient for initial planning needs. It is an interactive TurboBasic program which requires from the user an orbit altitude, inclination and number of orbits desired. Beginning sub-satellite latitude and longitude are 0,0. Outputs are orbit time in hours, minutes and seconds from time zero, latitude and longitude of that time and whether or not each TDRS is in view. There are forty time increments to an orbit, therefore each orbit altitude will yield a different time step. This program is valid for circular orbits only.

```
'
'
'
'
'
'              *************************
'              *  TDRS AVAILABILITY  *
'              *  PROGRAM FOR USER   *
'              *  SATELLITE PLANNERS *
'              *************************
'
'
'
```

```
'
'--------------------------------------------------INITIALIZE
'
CLS
OPEN "B:TDRAV.OUT" FOR OUTPUT AS 1
'
'
'-----------------------------------------------------INPUT
'
PRINT "THIS PROGRAM CALCULATES LINE OF SIGHT AVAILABILITY OF
TDRS-EAST"
PRINT "AND TDRS-WEST AS A FUNCTION OF USER INPUT ORBIT ALTITUDE
AND INCLI-" PRINT "NATION, AND NUMBER OF ORBITS. IT ALSO PROVIDES
INCREMENTAL SUB-"
PRINT "SATELLITE LATITUDE AND LONGITUDE FOR EACH DAY OF ORBIT.
STARTING"
PRINT "LATITUDE AND LONGITUDE ARE 0,0 AT TIME 0. OUTPUT FILE IS
TDRAV.OUT."
PRINT
PRINT
PRINT
PRINT
PRINT
INPUT "INPUT ORBIT ALTITUDE (KM)=";HO
PRINT
```

```
INPUT "INPUT ORBIT INCLINATION (DEG)=";I
PRINT
INPUT "INPUT DESIRED NUMBER OF ORBITS=";NO
'
'-------------------------------------------------SET CONSTANT VALUES
'
'
DEFSTR A
DEFDBL  J,T,U,C,P,R,D
A="  TDRS AVAILABILITY AS A FUNCTION OF SATELLITE ORBIT"
A1="****************************************************"
A2=" "
A3=" "
A4="ORBIT NO  DAY-HR-MIN   LAT    LONG   TDRS-E TDRS-W"
A5="  ##      ## ## ##    ####.#   ####.#    &      &  "
IF I=90 THEN I=89.9
J=.00108265
TD1=-41.0
TD2=-171.0
U=398601.2
CH1=319
CH2=189
PI=4*ATN(1)
RAD=PI/180
RE=6.378165E03
```

```
RO=RE+HO
RIN=RE/RO
CH3=(81.317/180) * PI + PI/2 - ATN(RIN/SQR(1-RIN^2))
T1=PI/30 * SQR(RO^3/U)
W1=2*PI/T1
W2=(1.5*J*SQR(U/RO^3)*RE/RO^2)/1440
W3=(.25-W2)*RAD
N=39
'
'-------------------------------------------------PRINT PARAMETERS
'
PRINT#1,A
PRINT#1,A1
PRINT#1, PRINT#1,
PRINT#1,
PRINT#1,"ORBITAL PARAMETERS USED"
PRINT#1,
PRINT#1, USING "ORBIT ALTITUDE=####### KM";HO
PRINT#1, USING "ORBIT INCLINATION=###### DEGREES";I
PRINT#1, USING "NUMBER OF ORBITS=#######";NO
PRINT#1, USING "TDRS EAST LONGITUDE=#######.## DEGREES ";TD1
PRINT#1, USING "TDRS WEST LONGITUDE=#######.## DEGREES";TD2
PRINT#1, USING "ORBIT PERIOD=#####.## MINUTES";T1
PRINT#1,
PRINT#1,
```

```
PRINT#1, A4
PRINT#1,
X1=COS(CH1*RAD)  : X2=COS(CH2*RAD)
Y1=SIN(CH1*RAD)  : Y2=SIN(CH2*RAD)
Z1=0 : Z2=0
'--------------------------------------------CALCULATE LAT/LON
'
FOR T=0 TO NO*T1 STEP T1/40
   X3=COS(W1*T)*COS(W3*T) + SIN(W1*T)*SIN(W3*T)*COS(I*RAD)
   Y3=-COS(W1*T)*SIN(W3*T) + SIN(W1*T)*COS(W3*T)*COS(I*RAD)
   Z3=SIN(W1*T)*SIN(I*RAD)
   N=N+1 : K=INT(N/40)
   D=INT(T/1440) : H=INT((T-1440*D)/60) : M=T-1440*D-60*H
   D1=X2*X3 + Y2*Y3 + Z2*Z3
   IF D1 > COS(CH3) THEN A2="*"
   D2=X1*X3 + Y1*Y3 + Z1*Z3
   IF D2 > COS(CH3) THEN A3="*"
   LA=(ATN(Z3/SQR(1-Z3^2)))/RAD
   LN=(ATN(Y3/X3))/RAD
   IF X3>0 AND Y3<0 THEN LN= 360 + LN
   IF X3<C AND Y3>0 THEN LN= 180 + LN
   IF X3<0 AND Y3<0 THEN LN= 180 + LN
   LT=INT(LA*10+.5)/10 : LM=INT(LN*10+.5)/10
PRINT#1,USING A5 ;K,D,H,M,LT,LM,A3,A2
A2=" " : A3=" "
```

```
NEXT T
CLOSE
END
```

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Naval Postgraduate School
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